National Library of Canada
Bibliothèque nationale du Canada

Canadian Theses Service
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtoût si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

NL-339 (r. 88/04) c

Canada

THE UNIVERSITY OF ALBERTA

USE OF THE NYLON BAG IN SITU TECHNIQUE AND PASSAGE RATE CONSTANTS IN PREDICTING VOLUNTARY INTAKE AND APPARENT DIGESTIBILITY OF FORAGES BY RUMINANT ANIMALS

BY

MARINA ANDREA GRAEFIN VON KEYSERLINGK

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

ANIMAL NUTRITION

DEPARTMENT OF ANIMAL SCIENCE

EDMONTON, ALBERTA

SPRING 1989

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-52779-X

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: MARINA ANDREA GRAEFIN VON KEYSERLINGK

TITLE OF THESIS: USE OF THE NYLON BAG IN SITU TECHNIQUE AND PASSAGE RATE CONSTANTS IN PREDICTING VOLUNTARY INTAKE AND APPARENT DIGESTIBILITY OF FORAGES BY RUMINANT ANIMALS

DEGREE: MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED: SPRING 1989

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it maybe printed or otherwise reproduced without the author's written permission.

M. v. Keyserlingk

RR#1 Site 20 Comp 28
Vernon B.C. V1T6L4

Date. November 17, 1988

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **USE OF THE NYLON BAG IN SITU TECHNIQUE AND PASSAGE RATE CONSTANTS IN PREDICTING VOLUNTARY INTAKE AND APPARENT DIGESTIBILITY OF FORAGES BY RUMINANT ANIMALS** submitted by **MARINA ANDREA GRAEFIN VON KEYSERLINGK** in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE in ANIMAL NUTRITION**.

G. W. Mathison

Supervisor

Peter D. McCalton

R. [illegible]

Date: November 17, 1988

DEDICATION

To my parents

Alexander and Ingeborg von Keyserlingk

ABSTRACT

The in situ bag technique was evaluated as a method of predicting the voluntary intake and digestibility of forages. Nine feedstuffs, including three cereal straws, three alfalfa/grass hay mixtures, two alfalfa/grass silages and a prairie hay were examined and in situ results were expressed in terms of the soluble, slowly degradable, and undegradable dry matter (DM) and rates of degradation were measured. Rates of passage of particulate and fluids through the digestive tract were also measured to determine if inclusion of information on the dynamic nature of digestion would improve predictions.

When these forages were fed to steers (350 ± 49.5 kg) voluntary DM intakes ranged from 1.00 to 2.85 kg 100 kg^{-1} body weight for the forage component of the feed. Apparent DM digestibilities ranged from 37 to 64%. At the maintenance feeding level fractional rates of particulate passage through the digestive tract were influenced by feed quality; values ranged from 0.020 to 0.023 for straws whereas the highest rate of 0.037 was measured for alfalfa/grass hay. No consistent effect ($P>0.05$) of forage quality on particulate passage rates were found at the highest feeding level nor were passage rates affected by feeding level. Steers fed one of the silages had the fastest fluid passage rate (0.060) and those fed barley straw the slowest passage rate (0.040) at the maintenance feeding level.

Prediction of DM digestibiity and voluntary intake from in

situ results was most accurate when residues from single in situ incubation times were used (R^2=0.92 at 24h and R^2=0.86 at 36h for DM digestibility and intake, respectively). Prediction equations based on the neutral detergent fiber content of feed resulted in coefficients of determination of 0.86 and 0.85 for DM digestibility and voluntary forage DM intake, respectively. The inclusion of information on rates of passage in prediction equations did not ($P>0.05$) improve predictions over those obtained using only chemical feed components or in situ bag results.

In conclusion, the use of the in situ technique for predicting intake and digestiblity cannot be recommended at the present time because of the time and expense involved and because these parameters can be predicted as accurately by simpler procedures.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my graduate supervisor Dr. J. W. Mathison for without his patience, encouragement and understanding this work would not have been possible. Dr. M.A. Price and Dr. J. R. Thompson are thanked for their encouragement to keep me going when times were tough.

The farm staff at Ellerslie, Mrs. Joanne Walker, Mr. Steve Melnyk, Mr. Julien Daniel and Tracy Stallard are also thanked for their help with the animals especially with all of the sampling that had to be done. For the [illegible]teful. The staff at the metabolic unit are thanked for their help in feeding and caring of the animals during the nylon bag trial. Mrs. Kay Olsen and Mrs. Pat Marceau were invaluable in the laboratory when the time came to analyse the hundreds of samples. Mrs. Irena Vlach was irreplacable when it came to entering the data into the computer and for the calculations required for the Ellerslie data.

The assistance of Mr. Gavin Godby and Mr. Ray Weingardt for help in statistical analysis is also gratefully acknowledged.

My sincere thanks are expressed to my collegue Eduardo Beltranena. Firstly, for his friendship and secondly for the numerous hours spent in helping me prepare the figures for the thesis.

I would also like to express my thanks to any staff and fellow graduate students who helped at one time or another for their help and in particular for the support and friendship shown by Valoree

Walker, Angela Bork and Erasmus Okine. I would also like to thank my sisters, Tinka and Gesa von Keyserlingk, and my cousin Mechthild Borsch for their constant phone calls which always seemed to come at exactly the right time.

Last but not least, there is my husband Nicholas Schmaling, whose constant love and support were irreplacable. The dedication in travelling out to Ellerslie every midnight to help collect samples and for the uncountable hours spent helping in the laboratory are gratefully appreciated.

Who wills can
Who tries does
Who loves lives

(Anne McCaffrey)

TABLE OF CONTENTS

CHAPTER		PAGE
I	GENERAL INTRODUCTION	1
	1.1 NYLON BAG TECHNIQUE	2
	1.1.1 AVANTAGES AND DISADVANTAGES	2
	1.1.2 PREDICTION OF INTAKE	6
	1.1.3 PREDICTION OF DIGESTIBILITY	7
	1.1.4 FEED FRACTIONS DETERMINED BY THE IN SITU TECHNIQUE	10
	1.2 THE RATE OF PASSAGE	12
	1.2.1 IMPORTANCE	12
	1.2.2 EFFECTS OF FEED INTAKE, FIBER AND GRINDING ON RATE OF PASSAGE	13
	1.2.3 CRITICAL SIZE OF PARTICLES AND RATE OF PASSAGE	14
	1.2.4 EFFECT OF FEED SPECIFIC GRAVITY ON PASSAGE RATES	15
	1.2.5 METHODS USED FOR DETERMINING THE RATE OF PASSAGE	16
	1.2.5.1 TYPES OF MARKERS	17
	1.3 REFERENCES	22
II	USE OF THE NYLON BAG IN SITU TECHNIQUE AND PASSAGE RATE CONSTANTS IN PREDICTING VOLUNTARY INTAKE AND APPARENT DIGESTIBILITY OF FORAGES BY RUMINANT ANIMALS	33
	2.1 INTRODUCTION	33
	2.2 MATERIALS AND METHODS	35
	2.2.1 FEEDSTUFFS	35
	2.2.2 IN VIVO APPARENT DIGESTIBILITY, VOLUNTARY INTAKE, AND PASSAGE RATES	35

2.2.3 IN SITU DEGRADABILITY OF FEEDSTUFFS 38

2.2.4 CHEMICAL ANALYSIS 40

2.2.5 STATISTICAL ANALYSIS 42

2.3 RESULTS 43

2.3.1 VOLUNTARY INTAKE, DIGESTIBILITY AND RATES OF PASSAGE 43

2.3.2 FEED FRACTIONS AND DEGRADATION 44

2.3.3 PREDICITION OF INTAKE AND DIGESTIBILITY 48

2.4 DISCUSSION 51

2.4.1 PARTICULATE AND FLUID RATE OF PASSAGE 51

2.4.2 FEED FRACTIONS 54

2.4.3 PREDICTION OF INTAKE 56

2.4.4 PREDICITION OF APPARENT DIGESTIBITY 59

2.4.5 USE OF RATES OF PASSAGE IN PREDICTION EQUATIONS 61

2.4.6 CONCLUSIONS 62

2.5 REFERENCES 64

III GENERAL DISCUSSION 90

3.1 REFERENCES 93

APPENDIX A 95

LIST OF TABLES

Table	Description	Page
2.1	Composition of feed dry matter for in situ incubation	72
2.2	Animal weight and voluntary dry matter intake	73
2.3	The effect of forage type on the rate of passage of fluid and particulate matter and on the apparent digestibility of dry matter (DM), organic matter (OM), acid detergent fiber (ADF) and neutral detergent fiber (NDF) at the low and high levels of intake	74
2.4	Percentage of dry matter, neutral detergent fiber, and crude protein which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C), and rates of degradation (Kd) of slowly degradable fractions	75
2.5	Amount of neutral detergent fiber and crude protein which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C) expressed as a percentage of feed dry matter	76

2.6 Relationships between feed dry matter composition and percentage of dry matter (DM), crude protein (CP) and neutral detergent fiber (NDF) which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C) 77

2.7 Relationships between feed dry matter composition and amount of crude protein (CP) in fraction A (soluble), fraction B (slowly degradable) and fraction C (undegradable) and neutral detergent fiber (NDF) in fraction C expressed as a percentage of feed dry matter 78

2.8 Dry matter, neutral detergent fiber and crude protein residues (g g^{-1} incubated) at specific in situ incubation times 79

2.9 Prediciton of voluntary dry matter intake (kg per 100kg body weight 80

2.10 Prediciton of apparent digestibility (%) of dry matter at the low feeding level 81

LIST OF FIGURES

Figure — Page

Fig. 2.1 Quadratic relationship between percent neutral detergent (NDF) in feed and percent crude protein in fraction C (undegradable portion) (Y=-5.35*feed %NDF + 147.2: n=9, r^2=0.98, S.E.=3.71) 82

Fig. 2.2 Linear relationship between 24 hour in situ dry matter residue and voluntary dry matter intake (kg per 100 kg body weight) (Y=4.20 + 3.79*24 h dry matter residue: n=9, r^2=0.79, S.E.=0.346 83

Fig. 2.3 Linear relationship between percent neutral detergent fiber (NDF) content of feeds and dry matter digestibility (%) (Y=97.29 - 0.701*feed %NDF: n=9, r^2=0.86, S.E.=4.35 84

Fig. 2.4 Quadratic relationship between the rate of particulate passage (fraction h^{-1}) and voluntary dry matter intake (Y=-10.4 + 806*rate of passage - 12332*rate of passage^2: n=9, r^2=0.90, S.E.=0.253) 85

Fig. 2.5 Linear relationship between percent neutral

detergent fiber (NDF) content of feeds and dry matter digestibility (%) (Y=97.29 - 0.701*feed %NDF: n=9, r^2=0.86 S.E.=4.35 86

Fig. 2.6 Linear relationship between 24 hour dry matter residue and dry matter digestibility (%) (Y=88.03 - 62.7*24 h DM residue: n=9, r^2=0.92, S.E.=3.35 87

Fig. 2.7 Quadratic relationship between rate of particulate passage (fraction h^{-1}) and dry matter digestibility (%) (Y=-75.14 + 7823*rate of passage - 111338*rate of passage^2: n=9, r^2=0.72, S.E.=6.56 88

Fig. 2.8 Linear relationship between actual and predicted dry matter digestibility (%) calculated from the equation of Waldo et al. (1972): DM digestibility = fraction A + (fraction B*KdB)/(KdB + Kp) where Dm=dry matter, A=soluble fraction, B=slowly degradable fraction, Kd=rate if degradation of slowly degradable fraction and Kp is passage rate of particulate material (Y=13.76 + 0.885*Predicted: n=9, r^2=0.81, S.E.=4.98 89

I. GENERAL INTRODUCTION

Description of forages in terms of their degradation characteristics in the rumen appears to be a useful tool in feed evaluation primarily because the utilization of roughages in vivo is largely dependant upon the microbial degradation which takes place in the rumen (Hovell et al. 1986). The in situ nylon bag technique has received considerable interest as a useful tool in evaluating forages since it is said to give a reliable estimate of in vivo protein, dry matter (DM) and fiber degradation across a wide range of feedstuffs (Weakley et al. 1983; Stern et al. 1983). Estimates of ruminal availability profiles for DM, nitrogen and fiber utilizing the in situ technique have also been attempted (Nocek and Grant 1987). It is well recognized that one of the most useful aspects of the procedure is that rates of degradation of material in the rumen can be measured (Weakley et al. 1983; Nocek 1985) which is of considerable importance since digestion is a dynamic process in which time is of extreme importance (Mertens 1987). However, even though the importance of rate of passage of material through the digestive tract of the animal is also recognized (Stern and Satter 1984) and has theoretically been shown to affect predictions of digestibility, there are no experiments in which rates of passage have been used in conjunction with the in situ technique for predicting the voluntary intake and digestibility of forages.

1.1 Nylon bag technique

1.1.1 Advantages and disadvantages

In vivo digestibility trials have been considered to provide the most useful information concerning the nutritive value of a feedstuff. However, several problems are evident in the use of this method. Firstly, in vivo digestibility values cannot be applied to individual structures present in forages (Hovell 1985). Secondly, the single value obtained does not mimic the time related degradation process which occurs as a result of microbial digestion (Hovell 1985). In addition, in vivo trials are expensive and are lengthy to conduct.

The Tilley and Terry (1963) two-stage in vitro digestion procedure was the first of many in vitro procedures which attempted to predict in vivo digestibility from the incubation of small samples of feed. Possibly the greatest advantage of this methodology is that the incubations can be controlled and altered in a manner to determine effects of specific treatments (Broderick et al. 1988). Disadvantages concerning the in vitro system are that in vivo conditions are only simulated, rumen fluid is collected at a specific time (Monson et al. 1969), and there is incomplete recovery of the degradation products (Broderick et al. 1988).

The in situ bag technique was initially developed by Quinn et al. (1938) and involves the incubation of feedstuffs in synthetic nylon bags suspended in the rumen for varying periods of time (Ørskov 1982). The technique is versatile, can encompass many types of feedstuffs and gives a reliable estimate of in vivo

degradation under some circumstances (Stern et al. 1983). This procedure allows for the rapid testing of a range of test diets using a single basal ration. It is also a relatively quick and simple technique (Hovell 1985) and allows one to look at the relative effect of different rumen environments on feedstuffs (Ørskov 1982). Broderick et al. (1988) pointed out that the incubation environment used in situ more closely represents the in vivo environment than occurs with the in vitro incubation. It has been noted, however, that the in situ technique is better suited to providing relative measures rather than absolute values (Stern and Satter 1984).

Traditionally the in situ technique has been used to obtain rumen degradability measurements for crude protein and dry matter (Mehrez and Ørskov 1977; Weakley et al. 1983; Ha and Kennelly 1984; Nocek 1985). Many of the early workers who employed the in situ procedure withdrew the bags after 1-2 h incubation periods. This method failed to incorporate the time-related component of degradation. Mehrez and Ørskov (1977) suggested the use of nylon bags as a routine method for measuring the rate of protein degradation in basal feeds and in protein supplements. Hovell (1985) indicated that it would be of greater benefit to plot the degradation curves for a period of up to 100 h in order to ensure that potential degradation was complete. Rate of nitrogen degradation obtained using the in situ method may be lower than in vivo results (Broderick et al. 1988) for three reasons: 1) there may be a reduced apparent rate of nitrogen loss due to microbial growth within the bag (Nocek and Grant 1987), 2) the actual number of microorganisms within the

bag may be lower than what is reflective of the rumen environment (Meyer and Mackie 1986), and 3) the rapid removal of soluble, degradable protein results in residual protein left behind which is more slowly degraded than protein as a whole (Broderick et al. 1988).

A major disadvantage surrounding the in situ bag technique, then, is the incursion of material into the bag (Nocek 1985) since the validity of the procedure is dependent upon the assumption that the net loss from the bags only occurs during degradation (Broderick et al. 1988). Consequently, Nocek (1985) suggests there is a need for thorough rinsing and then the assumption is made that any materials entering the bag and any soluble feed material will be removed. Kennedy et al. (1984), however, reported that the content of bacteria in the situ bags increased with increased time of incubation. Another disadvantage of this technique is that the results from nylon bag studies can only be applied to the specific conditions in which the bags were incubated (P. Robinson pers. comm.). Other factors affecting in situ rumen degradability estimates that have been extensively studied are bag porosity and sample weight:bag surface area ratio (Uden et al. 1974; Mehrez and Ørskov 1977; Van Hellen and Ellis 1977; Playne et al. 1978), substrate particle size (Figroid et al. 1972) and animal diet effects (Ganev et al. 1979). A further problem with the in situ technique is that because of the variability involved a large number of bags are required in order to detect differences between treatments. Playne et al. (1978) indicated that 27 bags per treatment were required to ensure a probability of 90% of detecting a 5% difference in DM

digestion between treatments. Mathison et al. (1988) found that in order to obtain a reasonable confidence interval of 4 digestibility units (P=0.95) for the estimation of bromegrass DM digestibility in the rumen at a particular time they would have had to incubate approximately 18 bags in the rumen.

In calculating the effective degradability of a feed sample by the in situ bag technique the rate of passage of the solid material must be considered (Kristensen et al. 1982). For example, if the rate of passage out of the rumen is high, the time allowed for degradation is short thus a greater proportion of the feedstuff will escape degradation. The rate of passage can have a dramatic influence on the extent of degradation. Stern and Satter (1984) found that by assuming fractional solid dilution rates of 0.04, 0.05 and 0.06 per hour mean protein degradations would be 68.6, 65.3 and 62.0%, respectively. Similarly, Kristensen et al. (1982) found that an increase in outflow rate from 2.2 to 6.6% per hour resulted in a decrease in the effective degradability for fishmeal, soybean meal and cottonseed meal of 20, 18 and 14%, respectively. Ørskov and McDonald (1979) looked at the effect of the rate of passage on the estimation of protein degradability from a concentrate source fed as a supplement to a dried grass diet for sheep. They concluded that 69% of the soybean meal protein disappeared within 24 h when the animals were fed at restricted intake however with ad libitum intakes, which resulted in a faster rate of passage, the 24-h degradability was estimated to be 65%. Even though it is evident that the rate of passage can have a effect on the extent of ruminal

degradation researchers continue to assume values rather than determining them for a particular feedstuff. Stern and Satter (1984) stated that the use of actual rate of passage values may increase the accuracy of predicting ruminal degradation but there is no information in the literature in which measured rates of passage have been used in conjunction with in situ results to predict either voluntary intake or apparent DM digestibilities of forages.

1.1.2 Prediction of intake

Models for predicting dry matter (DM) intake have received a great deal of interest since intake is the most important variable affecting animal performance (Waldo and Jorgenson 1981). Static or steady state models have been shown to be useful for predicting intake based on physiological concepts such as long term intake regulation (Mertens 1987). Conrad et al. (1964) and Baumgardt (1970) both reported that long-term regulation of intake is dependent on dietary and animal characteristics. For example, when diets are fed that are low in fiber and high in digestible energy, intake is controlled by the animal's energy demand which is a function of animal characteristics. However, in the contrasting case where the diet is high in fiber and low in digestible energy, gut fill becomes the limiting factor with respect to feed intake (Conrad et al. 1964; Baumgardt 1970). Mertens (1987) also criticized theoretical equations in which the fiber content of the diet was used to predict intake since such equations were unable to accurately predict intake when diets were low in fiber. He thus suggested that addition of a

third component, the animal's behavior and metabolic intake responses to stimuli that are not controlled by gut fill and energy demand, must also be considered in predicting intake.

The involvement of nylon bags with respect to prediction of intake was first introduced by Chenost et al. (1970) who reported significant relationships between results from nylon bags incubated in the rumen and voluntary intake. They noted that voluntary intake had a similar correlation ($r = 0.82$) with the 12-h DM residue as did in vivo digestibility ($r = 0.79$). In contrast to these results, however, Hovell et al. (1986) found that 48-h degradability was more highly correlated with intake ($r = 0.90$) than was 12-h digestibility.

Ørskov et al. (1988) attempted to predict the voluntary intake of cattle from the degradation characteristics of roughages during in situ incubation. They were able to account for more than 90% of the variability in intake and growth rate when they included both the rate of degradation and the proportion of degradable DM in feeds into the multiple regression equations. Ørskov et al. (1988) concluded that more research is required in order to see how wide a range of forages their results encompass.

1.1.3 Prediction of digestibility

It has been well established that digestibility of forages varies considerably, not only between species of forages but also within one species (Aerts et al. 1977). Consequently, determination of digestibilities of forages is required for feed evaluation purposes. Since in vivo experiments are time consuming and

expensive, there is need for a simple technique to estimate digestibility.

Monson et al. (1969) compared the in vitro dry matter digestibility with nylon bag dry matter digestibility. The in vitro technique gave much better results than the in situ technique for low quality bermuda grass, however, the reverse was true for higher quality grasses.

Aerts et al. (1977) compared seven methods for predicting the organic matter digestibility of three different types of forages. These included tabular digestibility coefficients, Weende components, cell wall components, summative equations, true digestibility in vitro, two stage digestibility in vitro, and nylon bag digestibility. The coefficients of determination for the estimation of in vivo organic matter digestibility with nylon bag digestibilities were the highest and were 0.92, 0.79 and 0.90 for grass hay, silages and pellets, respectively. Chenost et al. (1970) attempted to predict the in vivo OM digestibility from 24-h incubation data and obtained satisfactory results. Bittante et al. (1988) stated that the 48-h single in situ incubation appeared to be an effective method to predict the OM digestibility.

A theoretical model predicting digestibility based upon feed fractions was introduced by Lucas and Smart (1959) and Lucas (1962) who proposed that if feeds could be described by their nutritive entities, defined as chemical fractions that were either digestible or indigestible, the total dry matter digestibility could be calculated as the sum of the digestible nutritive entities. It was

determined that the non-fiber portion of a feed has a relatively high, constant digestibility that could be predicted by taking the intercept constant in regression equations. This is a partial explanation for the success in using fiber content to predict digestibility (Mertens 1987). Van Soest (1967) proposed yet another method using a summative equation with detergent fibers to predict digestibility. Feeds were separated into ideal and non-ideal nutritive entities. The neutral detergent solubles represented the greatest proportion of the ideal nutritive fraction and Van Soest (1967) determined that these had a true digestibility of 98% with an endogenous loss of 12.9%.

Waldo et al. (1972) presented a simple model for predicting digestibility which included terms for the rates of passage and degradation. True digestibility was calculated as the fractional rate of digestion divided by the total fractional rate of disappearance due to digestion and passage. Mertens (1987) criticized this model since an implicit assumption was that the level of intake is relatively constant giving a relatively constant rate of passage. This assumption means that much of the variability in digestibility associated with the animal is not considered in the prediction equations whereas it is known that the digestibilities of feed constituents with slow rates of digestion, such as fiber, are dramatically influenced by the rate of passage (Mertens 1987).

Hovell et al. (1986) attempted to relate DM digestibilities in vivo to the degradation characteristics determined in situ. These researchers calculated the theoretical rumen retention time in which

the potential degradability of four hays equaled that determined in vivo. The results indicated that very different degradation times were necessary to achieve the in vivo digestibilities measured. For example, one of the hays which had a measured in vivo digestibility of 60.9% and a potential degradability of 76.2% would have required a rumen retention time of 23.2-h (assuming no post-ruminal digestion) to achieve the measured in vivo digestibility. This was in contrast with another hay which had an in vivo digestibility of 45.4% and a potential degradability of 45.7% as measured by the in situ technique. This feed would have had to stay in the rumen for 79.7 h to achieve this in vivo digestibility. Thus, although Hovell et al. (1986) suggested that in vivo digestibility can be described in part by degradation characteristics, a two fold problem occurs when attempting to equate degradation characteristics with in vivo digestibility: firstly, retention times in the rumen can vary with forage type and, secondly, increasing the retention time can theoretically improve the digestibility of some forages but will have no effect on other forages. It is thus evident that more complete models which include the rate of passage are required in order to accurately predict digestibility of forages.

1.1.4 Feed fractions as determined by the in situ technique

Waldo et al. (1972) put forth a theory in which the cellulose in the rumen was divided into two fractions, the potentially degradable and the undegradable fractions. Kempton (1980) described the soluble component of feed or nutrient to be that portion which

can be physically removed by washing the bags in water. He also identified the slowly degradable and non-degradable fractions by analyzing the relationship between the proportion of material remaining in the bag after washing with compartmental analysis. Similarly, Nocek and Grant (1987) characterized in situ DM, nitrogen and fiber digestion in terms of ruminal availability profiles. Dry matter and nitrogen was classified into three profiles: 1) the pre-ruminal disappearance portion which was soluble in water, 2) the insoluble potentially digestible fraction and 3) the nondigestible portion. The fiber fractions, acid detergent fiber (ADF) and neutral detergent fiber (NDF) were only expressed in terms of the latter two profiles since they were unable to detect a water soluble fraction.

Nocek and Grant (1987) reported that legumes had approximately 10-15% higher DM disappearance following washing than did grasses. Timothy hay tended to have a lower amount of pre-ruminal nitrogen washout than ensiled material. In terms of nondigestible NDF and ADF, alfalfa tended to have more than other forages, which was explained by the higher lignin concentration in the alfalfa. Lancaster and Patterson (1988) determined the soluble fraction of various feedstuffs by soaking the forage in water for 1 hour. Dry matter losses ranged from 4 to 19%. Wheat straw lost the least amount of dry matter and the alfalfa hays the greatest amount. These differences were attributed to the amount of nonstructural material in the feed.

Very little information was found in the literature concerning the undigestible fraction. Nocek and Grant (1987) estimated the

nondigestible DM fraction to range from approximately 15 to 25% for alfalfa hay, 10 to 15% for clover, 22 to 25% for orchard grass and 15 to 25% for timothy. These researchers also estimated the undigestible fractions for NDF, ADF and nitrogen. Alfalfa tended to have higher undigestible fractions for NDF and ADF than did the other forages.

1.2 Rate of passage

1.2.1 Importance

Research in the area of passage rates in ruminant animals has been extensive (Grovum and Williams 1973; Faichney and Griffith 1978; Faichney 1980). It has been well established that productivity of the ruminant animal is dependent of the rate of passage of feedstuffs through the digestive tract (Welch 1986) and the extent to which the feedstuff is degraded in the rumen (Faichney 1986). The physiological makeup of the rumen is such that there is a delay in the passage of fibrous material from the ruminoreticulum which allows microbial degradation to occur (Van Soest 1982). Increased rates of passage will reduce the time allowed for the processes of fermentation, microbial synthesis and absorption to occur and thus the extent of degradation will be reduced (Dixon et al. 1983). Clearly, the effect of feedstuffs on passage from the rumen is of vital importance in terms of determining the nutritive aspects of feeds.

Another aspect of ruminant nutrition which has been shown to be related to rate of passage is microbial efficiency. The relative

proportions of bacterial and potentially digestible organic matter in different digesta phases have been shown to be primarily influenced by the relationship of microbial efficiency to rate of passage (Owens and Goetsch 1988). Particulate passage rates have been shown to be more closely related to microbial efficiency than fluid passage rates (Owens and Goetsch 1988).

1.2.2 Effects of feed intake, fiber and grinding on rate of passage

An increase in feed intake usually results in a faster rate of passage of both the fluid and the particulate phase through the gastrointestinal tract (GIT) (Faichney 1986). Low rates of passage are thus associated with low intakes. Also, increasing the proportion of fiber in the diet has been shown to increase particulate rate of passage of grain based diets. Supposedly this is due to increased stimulation of the propulsive activity (Warner 1981). The effect of grinding on the rate of passage is not as well established. Faichney (1986) reported that grinding of forages causes an increase in the bulk density of a forage thereby increasing voluntary feed intake. Warner (1981) also reported that rate of passage increased with grinding. Balch (1950), however, reported that ground hay took longer to pass through the alimentary tract than long hay. Faichney (1983) and Weston and Hogan (1967) both reported that the mean retention time of ^{51}Cr-EDTA, a fluid marker, was significantly longer for lucerne hay that was ground. Campling and Freer (1962) reported little difference in the mean retention time of long and ground roughages in the digestive tract of dairy cows fed ad

libitum but they did observe decreases in passage rate when ground roughage was fed at restricted levels of intake.

1.2.3 Critical size of particles and rate of passage

Balch (1950) conducted one of the first intensive studies concerning the rate of passage through the digestive tract. By feeding dairy cows stained feed particles so that the undigested particles could be visually identified in the feces, he determined that smaller particles exited the rumen faster than larger particles. As a result of similar observations Poppi et al. (1980) devised the critical size theory for particles leaving the rumen which asserts that particles greater than a certain size rarely pass out of the rumen. Poppi et al. (1980) recognized the fact that the proportion of large particles leaving the reticulo-rumen of sheep may not be constant since Smith et al. (1965), Van Soest (1964) and Troelsen and Campbell (1968) indicated that the level of feed intake and the type of feed had an affect on the size of fecal particles. They also concluded that there was virtually no change in particle size once the particles had left the rumen. Faichney (1986), however, described the removal of particles from the rumen in terms of probability of the particle passing through the reticulo-omasal orifice.

In order for particles to exit the rumen there must be some sort of particle size reduction, particularly when fibrous feedstuffs are fed. Grovum (1988) states that anything that increases the rate of particle breakdown of forage material in the reticulorumen will

cause an increase in small particle production and consequently in rate of passage. The mastication process which takes place during the initial ingestion of the food plays an important role in particle size reduction (Welch 1986) and also has a major influence on bacterial fermentation and the subsequent release of soluble material from the feed (Bosch et al. 1988; Welch and Hooper 1988). Forages high in neutral detergent fiber require more chewing than do higher quality forages (Welch and Hooper 1988).

Chewing during rumination is also a major contributor to particle size degradation, resulting in increases in specific gravity of forages and in forage surface area available for microbial attack (Welch and Hooper 1988). Dulphy et al. (1980) reported that rumination reaches a maximum of approximately 600 min when low quality diets are fed. As the digestibility increases and the fiber content of the diet decreases, the amount of time spent ruminating also decreases (Ulyatt et al. 1986). Welch and Hooper (1988) reported that cows eating oat straw spent considerable more time chewing and ruminating (145-191 min kg^{-1} DM consumed) than did cows eating good quality hay (87-104 min kg^{-1} DM consumed) or grass silage (99-120 min kg^{-1} DM consumed).

1.2.4 Effect of feed specific gravity on passage rates

Campling and Freer (1962) looked at the effect of specific gravity of inert particles on the rate of passage in cattle. In roughage diets, particles with a specific gravity of 1.12 had a shorter mean retention time in the whole tract than particles of

smaller or greater specific gravity within the range of specific gravities of 1.02-1.40. Welch (1986) criticized this work claiming that there may have been confounding with sedimentation rate or change in hydration of the particles during their long laboratory procedures. He used plastic material to simulate fiber and concluded that material with a specific gravity less than 1 was heavily ruminated, thus was passed out of the rumen very slowly. Intermediate specific gravities (1.17 and 1.42) passed most rapidly whereas the most dense particles (1.77 and 2.14) exited the rumen more slowly with little mastication.

1.2.5 Methods used for determining the rate of passage

When studying passage rates and mean retention time it is common to use markers or cannulas (Church 1969) through which flow rates can be measured. Markers allow for a great reduction in time and labor costs (Van Soest 1982). In passage rate studies it is desirable to have measurements of both particulate and liquid fractions of digesta, since it has been established that they undergo relatively independent turnover rates (Uden et al. 1980). Evans (1981) reported that particles are retained longer than solutes in the digestive tract; in addition, separation between these fractions may occur during sampling. Consequently, markers have been devised to measure both the liquid portion and the particulate portion of the digesta. Markers used for estimating rates of passage and studies in digesta flow are administered as a single injection (Van Soest 1982).

Measurement of the rate of passage can be difficult since it is

essential that the marker is recoverable and that the rise and peak concentration is determined in order to calculate the rate of passage (Van Soest 1982). Traditionally when conducting rate of passage studies, either by collecting fecal or rumen samples, collection times have been numerous and thus the procedure involves a great deal of work. For example, collections were carried out at 3 h intervals for 72 h, at 6 h intervals for 72 h and then at 12 h intervals for 96 h in the research of Faichney (1975).

Flow of undigested particles can be measured at various stages along the digestive tract. The fractional outflow rate from the rumen can be determined by sampling through a rumen cannula. Aitchison et al. (1986), however, criticized this in regards to particulate markers since difficulties are often encountered in obtaining representative samples of rumen digesta which may result in less reliable estimates of rumen outflow rate. These problems can be alleviated, in part, by sampling from the feces where thorough mixing is easier (Aitchison et al. 1986). Work conducted by Okine and Mathison (unpublished) has shown that there is a significant correlation (R^2 = 0.49) between rate of passage measurements determined using fecal marker concentrations and outflow rate determined from rumen sampling.

1.2.5.1 Types of markers

A wide variety of markers have been used in estimating the various aspects of rumen function described above. Kobt and Luckey (1972) put forth the following criteria required for a marker

substance: (a) has no toxic physiological or psychological effects; (b) is neither absorbed nor metabolized within the GIT; (c) has no appreciable bulk; (d) mixes intimately with, and remains uniformly distributed within digesta; (e) has no influence on intestinal secretion, digestion, absorption or normal motility; (f) has no influence on the microflora of the GIT; and (g) has physiochemical properties which readily allow quantitative measurement.

Balch (1950) estimated the rate of passage of food particles through the digestive tract using stained undigested particles. This technique, however, has received less interest since it has been criticized as being laborious and time consuming and the obtained results have been questioned in terms of significance (Kobt and Luckey 1972). Campling and Freer (1962) used rubber and plastic particles with cattle and demonstrated the significance of particle size and specific gravity with respect to the retention time of particles in the GIT. Another particulate marker utilized by Chandler et al. (1964) was polyethylene. They reported this marker to be acceptable for digestibility trials in which it was infused on a continuous basis based on the percentage recovery of the polyethylene marker.

Metal oxides have also been used as faecal markers. Examples of such markers include chromic oxide, ferric oxide, and titanium oxide (Kobt and Luckey 1972). Chromic oxide has been extensively used as a particulate digestibility marker and values obtained have been reported to be comparable to the conventional method of total collection (Kobt and Luckey 1972). There have, however, been some

problems concerning its use as a fecal marker since there has been evidence of variation in marker recovery, diurnal variation in marker excretion and analytical difficulties (Kobt and Luckey 1972; Krysl et al. 1988).

Recently, interest has been focused on the area of chromium, cerium and cobalt as markers for measuring the rate of passage of digesta. Development of a technique for mordanting Cr and Ce to plant fiber is described by Uden et al. (1980). The Cr-mordanted fiber has proven to fulfil most of the criteria recommended by Kobt and Luckey (1972) for an ideal marker. Ce, however, was found to be unsuitable since it failed to bind sufficiently to the plant cell walls (Uden et al. 1980).

Ytterbium, a rare earth marker, has also received considerable attention as a particulate marker. Ytterbium can be applied to a feedstuff either one of two ways: 1) application by a spraying method (Allen 1982; Hartnell and Satter 1979) or, 2) application by immersing the feedstuff in a ytterbium solution (Martz et al. 1974). Allen (1982) criticized the first technique in that it is doubtful that all potential binding sites of the feedstuff will come in contact with the ytterbium. The probability of saturating the binding sites is decreased when the spray method is utilized. The immersion technique, however, maximizes the probability of binding site saturation (Allen 1982). Ellis et al. (1982) also advocates the immersion technique and recommends that the feedstuff be immersed for 12-24 h.

Dysprosium, another rare earth marker, has also been utilized

for rate of passage studies. As in the case of ytterbium there is considerable evidence that the rare earth element may migrate from one binding site to another with the extent of migration increasing with decreases in pH (Crooker et al. 1982).

Water soluble markers have also been used to study water balance and volume in the rumen (Kobt and Luckey 1972) as well as rate of passage. Measurements of rumen volume and dilution rate are very important since they have been shown to have an effect on feed intake, digestibility and length of time available for ruminal fermentation (Teeter and Owens 1983). Faichney (1975) indicated that in order for liquid markers to estimate output from the rumen they must be water soluble, nonabsorbable, innocuous and indigestible. Polyethylene glycol has been frequently used as a water soluble marker in studies of absorption in man and animals (Kobt and Luckey 1972). Recently, however, it has been shown that polyethylene glycol will precipitate when given with feeds high in tannins (Uden et al. 1980) and there have been problems with percentage recovery of this marker (Van Soest 1982). It is also believed that some water soluble constituents, possibly tannins, interfere with the turbidometric assay for polyethylene glycol (Teeter and Owens 1983).

Downes and McDonald (1964) proposed the use of chromium-ethylenediamine tetraacetic acid (Cr-EDTA) as a liquid marker. Cr-EDTA is absorbed at low levels to protein and particles and is very easy to analyze (Van Soest 1982). Co-EDTA, as described by Uden et al. (1980), has also proven to be a suitable marker for measuring the liquid fraction of rumen digesta. Another advantage

that arises with the use of Co-EDTA is the ability to utilize it simultaneously with chromium oxide or chromium-mordanted cell walls (Hart and Polan 1984) which allows for the simultaneous measurement of both liquid and particulate flow.

1.3 REFERENCES

Aerts, J. V., De Brabander, D. L., Cottyn, B. G. and Buysse, F.X. 1977. Comparison of laboratory methods for predicting the organic matter digestibility of forages. Anim. Feed Sci. Tech. 2:337-349.

Aitchison, E. M., Gill, M., Dhanoa, M. S. and Osbourn, D. F. 1986. The effect of digestibility and forage species on the removal of digesta from the rumen and the voluntary intake of hay by sheep. Brit. J. of Nutr. 56:463-476.

Allen, M. S. 1982. Investigation into the use of rare earth elements as gastrointestinal tract markers. MSc. Thesis, Cornell University, Ithaca, New York.

Balch, C. C. 1950. Factors affecting the utilization of food by dairy cows 1. The rate of passage of food through the digestive tract. Br. J. Nutr. 4:361-338.

Baumgardt, B. R. 1970. Control of feed intake and the regulation of of energy balance. A. T. Phillipson, ed. Physiology of digestion and metabolism in the ruminant. Oriel Press, Ltd., New Castle Upon Tyne, England.

Bittante, G., Ramanzin, M. Cozzi, G. and Spanghero. 1988. Estimation of the organic matter in vivo digestibility and of the metabolizable energy content of feedstuffs and byproducts by means of the fiber bag technique. J. Anim. Sci. (Suppl) 66:495.

Bosch, M. W., Janssen, I. M., van Bruchem, J., Boer, H. and Hof, G.

1988. Digestion of alfalfa and grass silages in sheep. 1. Rates of fermentation in and passage from the reticulorumen. Netherlands J. Agric. Sci. 26:175-185.

Broderick, G. A., Wallace, R. J., Ørskov, E. R. and Hansen, L. 1988. Comparison of estimates of ruminal degradation by in vitro and in situ methods. 66:1739-1745.

Campling, R. C. and Freer, M. 1962. The effect of specific gravity and size on the mean time of retention of inert particles in the alimentary tract of the cow. Brit. J. Nutr. 16:507-518.

Chandler, P. T., Kesler, E. M. and McCarthy, R. D. 1964. Use of polyethylene to measure nitrogen absorption in calves. J. Anim. Sci. 23:870 (Abstr.)

Chenost, M., Grenet, E., Demarquilly, C. and Jarrige, R. 1970. The use of the nylon bag technique for the study of forage digestion in the rumen and for predicting feed value. Pages 697-710. in Proceedings of the 11th International Grassland Congress. Surfers Paradise. University of Queensland Press St. Lucia, Australia.

Church, D. C. 1969. Digestive physiology and nutrition of ruminants. Vol 1. Digestive physiology. O.S.U. Books, Corvallis, Oregon.

Conrad, H. R., Pratt, A. D. and Hibbs, J. W. 1964. Regulation of feed intake in dairy cows. I. Change in importance of physical and physiological factors with increasing digestibility. J. Dairy Sci. 47:54-62.

Crooker, B. A., Clark, J. H. and Shanks, R. D. 1982. Rare earth

elements as markers for rate of passage measurements of individual feedstuffs through the digestive tract of ruminants. J. Nutr. 112:1353-1361.

Dixon, R. M., Kennedy, P. M. and Milligan, L. P. 1983. Measurement of volume and flow in the digestive tract. Pages 25-41 in Nuclear techniques for assessing and improving ruminant feeds. International Atomic Energy Agency, Vienna, Austria.

Downes, A. M. and McDonald, I. W. 1964. The chromium-51 complex of ethylenediaminetetraacetic acid as a soluble rumen marker. Br. J. Nutr. 18:153-162

Dulphy, J. P., Redmond, B. and Theriez, M. 1980. pp 103-122. Ingestive behaviour and related activites in ruminants. (ed. Y. Ruckebush and P. Thivend) In Digestive Physiology and Metabolism in Ruminants. AVI Press, Westort, CT.

Ellis, W. C., Lascano, C., Guerrero, J., Pond, K. and Matis, J. H. 1982. Particle size degradation and escape from the rumen. Fed. Proc. 41:343 (Abstr).

Evans, E. 1981. An evaluation of the relationships between dietary parameters and rumen solid turnover rates. Can. J. Anim. Sci. 61:97-103.

Faichney, G. J. 1975. The use of markers to partition digestion within the gastro-intestinal tract of ruminants. In Digestion and Metabolism in the Ruminant. (ed. I. W. McDonald and A. I. C. Warner) pp. 277-291. Armidale N.S.W. University of New England.

Faichney, G. J. 1980. The use of markers to measure digesta flow

from the stomach of sheep fed once daily. J. Agric. Sci. (Camb.) 94:313-318.

Faichney, G. J. 1983. Assessment of the protein value of ruminant feeds. Pages 191-210 (ed. G. E. Robards and R. G. Packman) in Feed Information and Animal Production. Farham Royal, U. K. Commenwealth Agricultural Bureaux.

Faichney, G. J. 1986. The kinetics of particulate matter in the rumen. (ed. L. P. Milligan, W. L. Grovum, and A. Dobson) Pages 173-195. In Control of Digestion and Metabolism in Ruminants. Proceedings of the sixth international symposium on ruminant physiology. 1984, Banff, Canada. A Reston Book.

Faichney, G. J. and Griffiths, D. A. 1978. Behaviour of solute and particulate markers in the stomach of sheep given a concentrate diet. Br. J. Nutr. 40:71-82.

Figroid, W., Hale, W. H. and Theurer, B. 1972. An evaluation of the nylon bag technique for estimating rumen utilization of grains. J. Anim. Sci. 35:113-122.

Ganev, G., Ørskov, E. R. and Smart, R. 1979. The effect of roughage or concentrate feeding and rumen retention time on total degradation of protein in the rumen. J. Agric. Sci. (Camb.) 93:651-656.

Grovum, W. L. 1988. Appetite, palatability and control of feed intake. (ed. W. C. Church) in The Ruminant Animal Digestive Physiology and Nutrition. Prentice Hall, New Jersey. A Reston Book.

Grovum, W. L. and Williams, V. J. 1973. Rate of passage of digesta

in sheep. 4. Passage of marker through the alimentary tract and the biological relevance of rate-constants derived from the changes in concentration of marker in faeces. Br. J. Nutr. 30:313-329.

Ha, J. A. and Kennelly, J. J.1984. In situ dry matter and protein degradation of various protein sources in dairy cattle. Can. J. Anim. Sci. 64:443-452.

Hart, S. P. and Polan, C. E. 1984. Simultaneous extraction and determination of ytterbium and cobalt ethylenediaminetetra acetate complex in feces. J. Dairy Sci. 67:888-892.

Hartnell, G. F. and Satter, L. D. 1979. Determination of rumen fill, retention time and ruminal turnover rates of ingesta at different stages of lactation in dairy cows. J. Anim. Sci. 48:381-392.

Hovell, F. D. DeB. 1985. Thoughts on roughage digestion by ruminants. The Rowett Institute Annual Report. 40:25-33.

Hovell, F. D. DeB., Ngambi, J. W. W., Barber, W.P. and Kyle, D. J. 1986. The voluntary intake of hay by sheep in relation to its degradability in the rumen as measured in nylon bags. Anim. Prod. 42:111-118.

Kempton, T. J. 1980. The use of nylon bags to characterise the potential degradability of feeds for ruminants. Tropical Anim. Prod. 5:107-116.

Kennedy, P. M., Hazelwood, G. P. and Milligan, L. P. 1984. A

comparison of methods for the estimation of the proportion of microbial nitrogen in duodenal digesta, and of correction for microbial contamination in nylon bags incubated in the rumen of sheep. Br. J. Nutr. 52:403-417.

Kristensen, E. S., Moller, P. D. and Hvelplund, T. 1982. Estimation of the effective protein degradability in the rumen of cow using the nylon bag technique combined with the outflow rate. Acta. Agric. Scand. 32:123-127.

Kobt, A. K. and Luckey, T. D. 1972. Markers in nutrition. Nutr. Abst. Rev. 42:813-845.

Krysl, L. J., Galyean, M. L., Estell, R. E. and Sowell, B. F. 1988. Estimating digestibility and faecal output in lambs using internal and external markers. J. Agric. Sci. (Camb.) 111:19-25.

Lancaster, C. M. and Patterson, J. A. 1988. Effect of forage sterilization method on rate and extent of fiber degradaton by ruminal bacteria. J. Anim. Sci. 66:1800-1806.

Lucas, H. L. 1982. Some theoretical aspects of estimating forage qualtiy. Presented at Amer. Soc. Agron. Meet. Mimeo, North Caralina State University.

Lucas, H. L. and Smart, W. W. G. 1959. Chemical composition and digestibility of forages. 16th Southern Pasture and Forage Crop Improvement Conf. pp 23-26.

Mathison, G. W., Jahn, H. G., Walton, P. D. and Milligan, L. P.

1988. Use of the in situ technique in the study of degradation of lucerne and smooth bromegrass genotypes. Grass and Forage Sci. 43:474-481.

Mehrez, A. Z. and Ørskov, E. R. 1977. A study of the artificial bag technique for determining the digestibility of feeds in the rumen. J. Agric. Sci. (Camb.) 88:645-650.

Mertens, D. R. 1987. Prediciting intake and digestibility using mathimatical models of ruminal function. J. Anim. Sci. 64:1548-1558.

Meyer, J. H. F. and Mackie, R. I. 1986. Microbiological evaluation of the intraruminal in sacculus digestin technique. Applied and Environmental Microbiology 51:622-629.

Monson, W. G., Lowrey, R. S. and Forbes, I. Jr. 1969. In vivo nylon vs two stage in vitro digestion. Camparison of two techniques for estimating dry matter digestibility of forages. Agronomy J. 61:587-589.

Nocek, J. E. 1985. Evaluation of specific variables affecting in situ estimates of ruminal dry matter and protein digestion. J. Anim. Sci. 60:1347-1358.

Nocek, J. E. and Grant, A. L. 1987. Characterization of in situ nitrogen contamination of hay crop forages preserved at different dry matter percentages. J. Anim. Sci. 64:552-564.

Ørskov, E. R. and McDonald, I. M. 1979. The estimation of protein degradability in the rumen from incubation measurements weighted according to the rate of passage. J. Agric. Sci. (Camb.) 92:499-503.

Ørskov, E. R. 1982. Protein nutrition in ruminants. New York, Academic Press.

Ørskov, E. R., Reid, G. W. and Kay, M. 1988. Prediction of intake by cattle from degradation characteristics of roughages. Anim. Prod. 46:29-34.

Owens, F. N. and Goetsch, A. L. 1988. Ruminal fermentation. (ed. W. C. Church) pages 145-171. In The Ruminant Animal Digestive Physiology and Nutrition. A Reston Book.

Playne, M. J. Khumnualthong, W. and Echeuarria, M. G. 1978. Factors affecting the digestion of oesophageal fistula samples and hay samples in nylon bags in the rumen of cattle. J. Agric. Sci. (Camb.)90:193-204.

Poppi, B. P., Norton, B. W., Minson, D. J. and Hendricksen, R. E. 1980. The validity of the critical size theory for particles leaving the rumen. J. Agric. Sci. (Camb.) 94:275-280.

Quinn, J. I., van der Warh, J. G. and Myburgh, S. 1983. Studies on the alimentary tract of merino sheep in South Africa. 4. Description of the experimental technique. J. of Vet. Sci. and Anim. Industry. 11:341-360.

Smith, G. E., Smith, W. H. and Beeson, W. H. 1965. Effects of different levels of cellulose in semi-purified diets for calves. J. Dairy Sci. 48:787-788 (Abstr).

Stern, M. D., Ortega, M. E. and Satter, L. D. 1983. Retention time in the rumen and degradation of protein supplements fed to lactating dairy cattle. J. Dairy Sci. 66:1264-1271.

Stern, M. D. and Satter, L. D. 1984. Evaluation of nitrogen

solubility and the dacron bag technique as methods for estimating protein degradation in the rumen. J. Anim. Sci. 58:714-724.

Teeter, R. G. and Owens, F. N. 1983. Characteristics of water soluble markers in ruminatns for measuring rumen liquid volume and dilution rates. J. Anim. Sci. 56:717-728.

Tilley, J. M. A. and Terry, R. A. 1963. A two stage technique for the in vitro digestion of forage crops. J. Brit. Grassl. Soc. 18:104-111.

Troelsen, J. E. and Campbell, J. B. 1969. The effect of majurity and leafiness on the intake and digestibility of alfalfa and grasses fed to sheep. J. Agric. Sci. 73:145-154.

Uden, P., Colucci, P. E. and Van Doest, P. J. 1980. Investigations of chromium, cerium and cobalt as markers in digesta. Rate of passage studies. J. Sci. Food. Agric. 31:625-632.

Uden, P., Parra, R., and Van Soest, P. J. 1974. Factors influencing reliability of the nylon bag technique. J. Dairy Sci. 57:622-623 (Abstr).

Ulyatt, M. J., Dellow, D. W., John, A., Reid, C. S. W. and Waghorn, G. C. 1986. Contribution of chewing during eating and rumination to the clearance of digesta from the rumenoreticulum. (ed. L. P. Milligan, W. L. Grovum and A. Dobson) Pages 498-530. In Control of Digestion and Metabolism in Ruminants. Proceedings of the sixth international symposium of ruminant physiology. Banff, Canada. A Reston Book, New Jersey.

Van Hellen, R. W. and Ellis, W. C. 1977. Sample container porosites for rumen in situ studies. J. Anim. Sci. 44:141-146.

Van Soest, P. J. 1964. Symposium on nutrition and forage and pastures: new chemical procedures for evaluating forages. J. Anim. Sci. 23:838-845.

Van Soest, P. J. 1967. Development of a comprehensive system of feed analysis and its application to forages. J. Anim. Sci. 26:1174-1175.

Van Soest, P. J. 1982. Nutritional ecology of the ruminant. O & B Books, Corvallis, Oregon.

Waldo, D. R., Smith, L. W. and Cox, E. L. 1972. Model of cellulose disappearance from the rumen. J. Dairy Sci. 55:125-129

Waldo, D. R. and Jorgensen, N. A. 1981. Forages for high animal production: nutritional factors and effects of conservation. 64:1207-1229.

Warner, A. C. I. 1981. Nutrition Abstracts and Reviews. Rate of passage of digesta through the gut of mammels and birds. 51(B):789-820.

Weakley, D. C., Stern, D. M. and Satter, L. D. 1983. Factors affecting disappearance of feedstuffs from bags suspended in the rumen. J. Anim. Sci. 56:493-507.

Welch, J. G. 1986. Physical parameters of fiber affecting passage from the rumen. J. Dairy Sci. 69:2750-2754.

Welch, J. G. and Hooper, A. P. 1988. Ingestion of feed and water. (ed. W. C. Church) Pages in The Ruminant Animal Digestive Physiology and Nutrition. Prentice Hall, New Jersey.

Weston, R. H. and Hogan, J. P. 1967. The digestion of chopped and ground roughages by sheep I. The movement of digesta through the stomach. Aust. J. Agric. Res. 18:789-801.

II. USE OF THE NYLON BAG IN SITU TECHNIQUE AND PASSAGE RATE CONSTANTS IN PREDICTING VOLUNTARY INTAKE AND APPARENT DIGESTIBILITY OF FORAGES BY RUMINANT ANIMALS

2.1 INTRODUCTION

Extensive work has revolved around the prediction of intake potential and digestibility of feeds from their chemical composition. This method of prediction has undergone criticism since intake and digestibility of feeds by ruminants are influenced not only by the chemical composition of feeds but also by the animal and feeding environment (Mertens 1987).

The use of the nylon bag technique for evaluating feedstuffs has become popular due to its simple and direct nature and because rates of degradation can be determined (Hovell 1985). It has also been extensively used to assess the digestibility of dry matter (DM) and protein in feed components (Playne et al. 1978; Figroid et al. 1982; Mehrez and Ørskov 1983). Aerts et al. (1977) compared seven laboratory methods for predicting the organic matter (OM) digestibility of forages and concluded that the nylon bag technique most accurately predicted OM digestibility when compared to in vivo values. Other researchers have not found the nylon bag technique as good as in vitro techniques for predicting digestibilities (Cote et al. 1982).

The use of results from nylon bag incubation for prediction of intake was introduced by Chenost et al. (1970). These researchers noted that voluntary intake had a high correlation (r = 0.82) with

the 12-h incubation data. This was similar to correlation (r=0.79) obtained with in vivo digestibility. Hovell et al. (1986) also reported that degradation of dry matter during short periods of nylon bag incubation were better correlated with voluntary intake than with in vivo digestibility. Ørskov et al. (1988), using nylon bags to predict the voluntary intake of straw by cattle from dry matter degradation characteristics, concluded that more than 90% of the variability associated with intake and growth could be described when the rate of degradation of dry matter was included with the potentially degradable fraction in the multiple regression equation. These researchers concluded that more research is required in order to see how wide a range of forages their results encompass.

The in situ bag technique appears to offer promise as a means of predicting the digestibility and voluntary intake of forages. Little data is available, however, in which the rate of degradation and the rate of passage are both measured and used to predict digestibility, and in which predicted animal responses are compared to actual results. This trial was thus conducted in order to further evaluate the predictive capabilities of the nylon bag technique when combined with mathematical models describing rumen function.

2.2 MATERIALS AND METHODS

2.2.1 Feedstuffs

Nine feedstuffs obtained from various locations in Alberta were used for this experiment (Table 2.1). The three straws consisted of wheat (Triticum aestivum L.) straw, wheat straw treated with liquid supplement and barley (Hordeum vulgare L.) straw. The supplement was a controlled-release 32% liquid protein supplement (Registration No. 620015, Nutrena Feeds, Cargill Limited, Winnipeg, Manitoba) which was added at a rate of 11.5% of the straw DM. Three alfalfa/grass hays had varying proportions of alfalfa (Medicago sativa L.) and smooth bromegrass (Bromus inermis Leyss.): 75% alfalfa and 25% smooth bromegrass (75/25), 65% alfalfa and 35% bromegrass (65/35), and 50% alfalfa and 50% smooth bromegrass (50/50). One sample of prairie (Festuca hallii L.) grass hay, commonly called prairie wool in Alberta, was included. Two alfalfa/grass silages (50% alfalfa, 45% bromegrass and 5% fescue (Festuca rubra L.)) were included in the experiment. The silage was prepared from the same forage crop with one sample being ensiled at 28% DM in a 3 m high pile which was covered immediately with polyethylene and sealed around the edges. The other silage sample (38% DM) had been preserved in a 2.4 m diameter polyethylene silo bag which was filled using a silage packer (Agric. Pac. 8 ft Pioneer Bagger, St. Clair Manufacturing, Nompa, Idaho 8351).

2.2.2 In vivo digestibility, voluntary intake and passage rates

Measurements were made in the Ruminant Feed Evaluation Unit (Mathison et al. 1984). Twenty growing Hereford steers weighing approximately 350 ± 49.5 kg were used in the evaluation. Five animals were randomly assigned per treatment. The daily feed requirements were divided into two equal portions and fed at 8:00 and 16:00. A preliminary adaptation period of 7 d was allowed in which the animals were fed a standard hay diet. The test feeds, which had been ground to approximately 5 cm through a tub-grinder (Model 390, Sperry New Holland, New Holland Pennsylvania), were then introduced and voluntary intake measurements were conducted during the last 7 d of the 17 d ad libitum period. Digestibility measurements were conducted at two feeding levels: firstly, a feeding level of approximately two times maintenance (or at 90% ad libitum intake if this feeding level could not be attained), and secondly, at the maintenance feeding level. In each case there was a 10-d adjustment period followed by an 8-d total collection period.

Evaluation of the nine feeds used in this experiment occurred over a period of 6 months (July 1987 to December 1986). Only two forages were analyzed at one time because of limitations in metabolic crates and chambers. Forages were grouped in the following manner: wheat and wheat + supp, 75/25 and 65/35 hays, 50/50 hay and prairie hay, and the two silage samples. Barley straw was analyzed along with treated barley straw but this latter feed was not analyzed in the in situ trial consequently results from the animal work are not given.

Steers fed straw were supplemented with barley grain, fed at

15% of the intake of straw DM consumed the previous day. In addition they received an amount of the liquid supplement equal to 11.5% of straw DM. The supplement was either mixed with the straw at the time of harvest (wheat + supp) or fed with the grain (wheat). In order to calculate digestibilities for straw alone average values for DM, organic matter (OM), crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) digestibilities for barley grain were calculated from five different barley grain samples previously analyzed in the Feed Evaluation Unit (DM-82.8%, OM-84.2%, CP-78.3%, NDF-44.5%, ADF-28.3%). Also the liquid supplement DM and OM was considered to be 80% digestible and to contain 0% fiber.

Four animals from each group were given markers on the morning of the first day of the fecal collection period, immediately prior to the morning feeding. Cobalt-ethylenediamine tetraacetic acid (Co-EDTA), a liquid marker prepared according to the procedure described by Uden et al. (1980), was administered (5 g of Co or 37.5 g Co-EDTA). The Co-EDTA was dissolved in 1 L of water and flushed down a Rheinhard oral tube. Following administration of the marker, 2 L of water was flushed down the tube in order to ensure that all of the marker entered the animal. Occasionally animals regurgitated some rumen contents while being tubed.

Chromium-mordanted fiber (approximately 3 g Cr or 100 g of mordanted fiber), also prepared according to the methodology described by Uden et al. (1980), was used as the particulate marker. The chromium-mordanted fiber was mixed with a small portion of the test feedstuff and fed to the animals. The marker was readily

consumed within a very short time.

Fecal samples for the marker estimation were taken concurrently with the total collection of feces. Marker fecal sample collection for the three straw diets began 8 h following administration of the markers with other samples being collected at 11, 14, 20, 23, 26, 29, 32, 35, 38, 44, 47, 50, 53, 56, 59, 62, 68, 74, 80, 86, 92, 104, 116, 128, 140, 152, 164 and 176 h. The 75/25 and 65/35 alfalfa hay diets had a similar sampling regime (8, 14, 20, 23, 26, 32, 38, 44, 50, 56, 62, 70, 74, 78, 94, 102, 118, 126, 142, 150, 166 and 174 h). The rate of passage for the other four feeds were determined by dosing at 0 h and sampling every 24 h for 8 days. It is assumed that one defecation occurred at the midpoint of each interval in which faeces was collected (Faichney 1980). Prior to analysis for marker concentrations the feacal samples were dried at 60 C and ground using a coffee grinder. Rates of passage were calculated at the rate of decline in the natural logarithm of cobalt or chromium concentration in the feces following peak concentration.

2.2.3 In situ degradability of feedstuffs

Three ruminally cannulated steers (600 Kg) fed 9 kg d^{-1} brome/alfalfa/timothy hay in two equal feedings, were used for the in situ incubations. The nine feeds were divided into three groups: 1) three straws, 2) three alfalfa/grass hays, and 3) prairie hay plus the two silages. Each group of feeds was placed in a different animal during each of three different incubation periods. The two silage samples were dried at 60 C for 48 h in a forced-air oven

before incubation. All feeds for in situ incubation were ground through a 3 mm screen. Bags measuring approximately 3.5 x 5.5 cm were prepared from Nytex (B.S.H. Thompson, Scarbourough, Ontario) which had an average porosity of 48 um, and filled with approximately 1 g feed (air-dry). The ratio of sample weight to bag area was 26 mg cm^{-2}. Bags were heat-sealed by the method of de Boer et al. (1987).

A total of twenty bags (two duplicate bags per time of incubation) for each feedstuff were prepared and eighteen were suspended in the rumen in a polyester mesh bag which was suspended on the end of a 50 cm line weighted with a sand-filled bottle (de Boer et al. 1987). Samples were incubated for 0, 4, 8, 12, 24, 36, 48, 72, 96, and 120 hours. The bags were introduced into the rumen in reverse sequence, that is the 120-h bags were placed into the rumen first, then the 48-h bags, etc. This procedure was followed in order to minimize the time that the bags already in the rumen were exposed to air and to enable the washing of all bags simultaneously in the mechanical bag washer described by de Boer et al. (1987). Washed nylon bags were separated into two groups. One bag for each group was dried in a forced air oven at 110 C to a constant weight for DM determinations. These bags plus their contents were also subsequently used for crude protein (CP) determination. Empty bags were used as blanks to correct for the nitrogen content of the bags. The other group of bags were analyzed for NDF.

Material that could be washed from the 0-h bags not incubated in the rumen was considered to be the soluble (A) fraction. Fraction

C was the undegraded residue left in the bag after 120-h ruminal incubation. For DM and protein the slowly degraded (B) fraction was calculated as the difference between the material put in the bag and fraction A plus C. In the case of NDF, fraction B was calculated as 100 minus fraction C. Rates of degradation of fraction B were calculated after 8 h incubation from the slope of the regression of the natural logarithm of the residue minus the residue in the bag at 120 h against time (Mertens and Loften 1980). The procedure of Mertens and Loften (1980) was also used to estimate lag time however there was no significant effect lag time for any of the feeds.

2.2.4 Chemical analysis

Dry matter determinations were conducted on all samples by drying approximately 1 g of the ground samples at 110 C until a constant weight was reached. Crude protein (nitrogen x 6.25) was determined using the Kjeldahl procedure (Association of Official Analytical Chemists (AOAC) 1980; procedure #2.057). Neutral detergent fiber, ADF and lignin were analyzed according to the methodology of Goering and Van Soest (1970) except for residual NDF in bags. For this analysis, 45 bags (washed in water but not dried) were placed in a 4 L glass beaker containing NDF solution (60 mL per bag) and boiled vigorously for 1 h. A condenser (1 L round bottom flask in which cold water entered and exited via 1 cm diameter tubing) was placed on the beaker in order to prevent any concentration of NDF solution. Following completion of the boiling phase, bags were rinsed briefly with cold water under a running tap

and then placed in a nylon stocking and rinsed twice using hot water in a conventional washing machine. The bags were then dried to a constant weight at 110 C and weighed to determine the neutral detergent residue. Analysis for calcium and total ash were by AOAC methods (AOAC 1980; procedures 7.097 and 7.009, respectively). Phosphorus was analysed by colorimetry (Technicon Autoanalyser II 1978). Acid detergent insoluble nitrogen (ADIN) was determined by the method of Goering et al. (1972).

The procedures for determination of fecal cobalt concentrations involved first ashing 0.5 g of fecal material at 500 C overnight. The ashed sample was allowed to cool and then 5 mL of 4 N HCl was added and the mixture allowed to sit for 30 min at room temperature. The solution was then diluted with 15 mL deionized water and subsequently centrifuged at 1000 x g for 15 min. Absorption of cobalt was read using an acteylene flame with a Perken Elmer spectrometer (model 4000 Perkin-Elmer Corporation Norwalk, CT).

Chromium samples were prepared by weighing 0.5 g fecal material into a weighed 50 mL Erlynmeyer flask. Thirty mL of 4 M HNO_3 was added and the sample was left for 4 h at room temperature. The flasks were then heated to 75 C for 12 h, cooled and the gross weight determined so the amount of remaining solution could be calculated. The sample was transferred to a centrifuge tube and centrifuged at 10,000 x g for 10 min. The supernatant was removed with a pasture pipette, diluted (1:10 vol/vol) with deionized water when necessary, and the absorption of Cr was determined using atomic absorption spectroscopy.

2.2.5 Statistical Analysis

The experimental design for the in situ procedure was a 3 X 3 latin square design with three groups of feeds with three feeds in each group (Winer 1971). The effects of feed (n=9), period (n=3) and animal (n=3) were considered in the analysis of variance procedure. The residual (d.f.=68) was used as the error term.

An incomplete randomized block design was used for in vivo measurements and least square means were determined with high (error df = 20) and low (error df = 32) feeding levels being analyzed separately. Feeds (n=6 for high feeding level and n=9 for low feeding level) were the only sources of variation considered thus differences were confounded by period effects.

Simple, multiple and quadratic regressions were calculated using in vivo and in situ results and coefficients of determination (R^2) and standard errors of estimates were calculated according to procedures outlined in Steel and Torrie (1980).

2.3 RESULTS

The chemical compositions of the feedstuffs used for in situ incubation are given in Table 2.1. The crude protein content ranged from 4-15%, NDF from 44-82%, and ADF from 30-48%. However, lignin content of feeds did not vary to a great extent. Acid detergent insoluble nitrogen (ADIN), an indication of extent of heat damage, varied from 0.15-0.25% of roughage DM. The liquid supplement increased the CP, Ca and P content of the wheat straw. Silage preserved at 37% DM had more CP and slightly less fibre and ADIN than silage preserved at 28% DM.

2.3.1 Voluntary intake, digestibility and rates of passage

Voluntary DM intakes of forages ranged from 3.0 to 11 kg d^{-1}. Intakes were lowest when the straw diets were fed but the animals were also smaller when fed these diets (Table 2.2). The intake of the three straw diets has been given for straw only and does not include intake of barley grain or supplement. Data of Mathison (1974) suggests that intake of straw does not change when small amounts of supplemental grain is given. The effect of forage type on the apparent digestibilities of DM, ADF, NDF and OM are given in Table 2.3. As expected, the straws gave the lowest digestibilities, with apparent DM digestibilities ranging from 37 to 43%. The apparent DM digestibility of prairie hay was 44% whereas the other hays and silages were 58-64% digestible. No digestibility data is available for straw diets at high intakes because animals

would not voluntarily consume more than the maintenance feeding level.

At the low feeding level the fractional particulate passage ranged from 0.020 to 0.037 h^{-1}, with no significant differences being detected except between the 37% DM silage (0.037) and the treated wheat straw (0.022) and barley straw (0.020) (Table 2.3). The 37% DM silage diet also had the fastest passage rate at the high feeding level (0.042 h^{-1}) which was higher ($P<0.05$) than the particulate passage rates for native hay (0.025), the 65/35 hay (0.031) and the 28% DM silage (0.032). The only change in the particulate passage rates caused by increased intake was with the 75/25 hay where animals at the high level of intake had a significantly ($P<0.05$) faster rate of passage than those at the low level of intake.

The effect of forage type on the fluid rate of passage is presented in Table 2.3. The 28% DM silage (0.060) had the fastest ($P<0.05$) rate of fluid passage and the barley straw the slowest (0.040) at the low level of intake. There were no differences ($P>0.05$) between feeds at the high level of intake. The effect of intake on the fluid fraction was also only significant for the 65/35 hay, where passage rates at the low feeding level was higher ($P<0.05$) than at the high level of intake (0.054 vs 0.045).

2.3.2 Feed fractions and degradation

The percentage of DM, NDF and CP which was soluble (fraction A), slowly degradable (fraction B) and nondegradable (fraction C),

and rates of degradation (Kd) of the slowly degradable fractions, are given in Table 2.4. The two silage samples had the highest ($P<0.05$) proportion of their DM in fraction A (30-33%). The 65/35 hay contained more ($P<0.05$) soluble DM (27%) than other hays or straws whereas the two untreated straw samples had significantly less ($P<0.05$) soluble DM (6 and 7%) than the prairie hay sample (12.5%) (Table 2.4). It is of interest that there was no significant difference in the proportion of CP in fraction A between the two silage samples and the treated wheat straw (Table 2.4) although there was more total soluble CP in the silages (Table 2.5). The three alfalfa grass hays did not differ in either the proportion (23-34%) or total amount of CP (Table 2.5) which was soluble.

The percentage of DM material that was slowly degradable (fraction B) was higher ($P<0.05$) in the prairie grass sample (54%) than in the two wheat straws (38-40%) (Table 2.4). No significant difference was observed between any of the other feedstuffs with respect to the slowly degradable DM fraction. Prairie hay and the three hays had a significantly greater percentage of their CP in the slowly degradable fraction B (47-61%) than the straws and the silages (Table 2.4). There was no difference ($P>0.05$) between the rest of the feeds in terms of the percentage of slowly degradable CP. When slowly degradable CP was expressed in terms of total amount in the feed (Table 2.5), the hays had the highest amount, the silages the next highest and the straws the least.

The straws all had significantly ($P<0.05$) greater

percentages of fraction C DM (50-55%) than the other feeds (25-37%) (Table 2.4). Prairie hay, 75/25 and the 50/50 hay had significantly ($P<0.05$) less undegradable DM than the straws but more than the 65/35 hay and the two silages. The percentage of NDF in fraction C ranged from 28 to 62 (Table 2.4). Straws had the highest percentage of nondegradable NDF (53-57%) and the silages the lowest (28-38%). The amount of fraction C NDF expressed as a percentage of feed DM (Table 2.5) ranged from 41-47%, 21-31% and 15-22% for straws, hays and silages, respectively. Untreated straws had the highest ($P<0.05$) proportion of CP in fraction C whereas alfalfa/grass hays and silages had the least (Table 2.4). There was no difference ($P>0.05$) in fraction C CP between feeds when this was expressed as a percentage of feed DM (Table 2.5).

The rates of degradation of the slowly degradable DM, NDF and CP are given in Table 2.4. The only observed differences were that the 65/35 and 75/25 hay samples had significantly ($P<0.05$) faster rates of DM degradation (0.055 and 0.059 h^{-1}) than the other samples (0.024 to 0.044 h^{-1}).

Linear and quadratic relationships between feed composition and the proportion of DM, NDF and CP which was soluble, slowly degradable and undegradable NDF and CP are given in Table 2.6. Fraction A DM was most closly related to feed CP and NDF (R^2=0.91 and 0.97, respectively) whereas only 54-72% of the variation in fraction C DM was explained by feed components. The proportion of CP in fraction A was not significantly related to feed composition

(Table 2.6) however fraction B CP decreased ($P<0.05$) with increasing fiber content of the feedstuff (Table 2.7). Fraction C CP was directly correlated with the fiber content of the feed and its prediction was improved if quadratic equations were used (Fig. 2.1). It was not possible to accurately predict the percentage of nondegradable NDF from feed components.

The relationship between feed composition and the amount of fraction A, B and C NDF and CP in feed DM is examined in Table 2.7. It was possible to gain some information from the chemical analysis concerning the feed with ADF being the best predictor for fraction B and C CP as a percentage of DM (R^2=0.78 and 0.82, respectively). The proportion of fraction C NDF expressed as a percentage of feed DM was most closely related (R^2=0.71) to feed NDF (Table 2.7).

Dry matter, NDF and CP residues at each individual time of incubation are given in Table 2.8. As expected the three straws had the most ($P<0.05$) DM residue, the prairie hay was intermediate and the hays and silages had the least amount of residue at each time of incubation. More NDF was measured in the bags than was put into the bags for times of incubation up to 12 h for straws and hays. Efforts were made to account for the increased NDF content by repeating the washing and NDF procedure on new 0-h bags. Rather than washing and analyzing all bags together they were washed individually under running tap water until the water became clear and then cut open and analyzed individually for NDF content, however, the problem was not solved. It was thus concluded that the increased NDF content may have been because samples used for in situ incubation had been ground

to 3 mm whereas the samples used for feed analysis had been ground to 1 mm thus increasing the surface area for exposure to the NDF solution. The straws and the alfalfa hays had the greatest proportion of NDF left in bags at most incubation times whereas native hay and silages had the least ($P<0.05$). The proportion of CP remaining in the bags was generally the highest for the untreated straws, with the crude protein in native hay and treated straw being the next most resistant to degradation (Table 2.8). There was little difference between the alfalfa hays and silages in terms of residual CP remaining in bags at various incubation times.

2.3.3 Prediction of intake and digestibility

In the case of prediction of intake the 36-h single incubation time gave the best prediction ($R^2=0.86$), however, the 12, 24, 48, 72 and 96-h incubation times gave only slightly lower coefficients of determination $R^2=0.72$, 0.79, 0.80, 0.79 and 0.75, respectively (Table 2.9; Fig. 2.2). Results from the 120-h sampling time did not explain as much of the variability in intake ($R^2=0.67$).

Table 2.9 (and Appendix A) gives the relationship between voluntary DM intake and feed composition and degradation characteristics of the feeds. The percentage of NDF (Fig. 2.3), ADF and CP in feeds could be used to predict voluntary DM intake ($R^2=0.85$, 0.85 and 0.71, respectively). The individual times of in situ incubations also worked with reasonable accuracy for predicting intake and digestibility. These predictions were not improved ($P>0.05$)

when the proportions of DM in fractions A, B or C, or rates of digestion and passage (at the low feeding level) were considered. The use of the rate of particulate passage constants to predict intake worked reasonably well in a quadratic relationship resulting in a coefficient of determination of R^2=0.90 (Fig. 2.4). Rates of fluid passage, however, were of little use in prediction equations estimating intake (R^2=0.59). The addition of the rate of degradation or the rate of particulate passage in the prediction equations with the potentially degradable DM fractions (A+B) of the feeds dramatically strengthened the ability to predict voluntary intake (R^2=0.63 vs 0.86 and 0.77, respectively).

Predictions, using regression equations, of DM digestibilities are presented in Table 2.10. Feed NDF (Fig. 2.1) and CP gave highly significant ($P<0.01$) relationships (R^2=0.86 and 0.77, respectively) with digestibility whereas feed ADF was slightly less well related (R^2=0.60). Prediction of apparent digestibility using single in situ incubation times worked with a high degree of precision (Table 2.10). The 24-h (Fig. 2.6) and 36-h single in situ incubation used to predict DM digestibility resulted in coefficients of determination of 0.92 and 0.89, respectively whereas the other DM residue times also worked with reasonable accuracy (R^2=0.71 to 0.86). The use of the proportion of feed DM in the soluble and slowly degradable fractions (A + B) to predict digestibility also gave a significant ($P<0.05$) relationship (R^2=0.69). The use of the rate of particulate passage to predict DM digestibility did not improve the coefficients of determination (R^2=0.72; Fig. 2.7) nor did the use of fluid rate of passage

(R^2=0.46). The incorporation of the rate of degradation and the rate of passage into the prediction equations along with fractions A + B resulted in significant ($P<0.05$) improvements in the ability to predict DM digestibility (R^2=0.87 and 0.76, respectively). However, the inclusion of either rate of passage or rate of digestion did not improve the relationship above that obtained using feed CP or NDF to predict DM digestibility (Table 2.10).

2.4 DISCUSSION

This experiment allowed for the evaluation of a wide range of forages in growing animals. Unfortunately all feeds could not be evaluated in vivo at one time thus the relation between chemical and in situ results with digestibility and intake may have been affected by period effects. Voluntary intake comparisons across feeds would likely have been affected to the greatest extent, with straw diets being consumed by the animals when they were younger and smaller. Digestibility in ruminants is not influenced much by age when animals have a functional rumen (Schneider and Flatt 1975). It was also unfortunate that the animals were unable to consume enough of the three straw diets in order to evaluate the feedstuffs at a higher level of intake.

2.4.1 Particulate and fluid rate of passage

Rates of passage were measured in the whole tract rather than directly in the rumen because the use of fistulated animals could not be accommodated within the Ruminant Feed Evaluation Unit procedure (Mathison et al. 1984). Pond et al. (1983) suggested that passage rates determined for the whole digestive tract would be similar to passage rates from the ruminoreticulum. The validity of using whole tract rate of passage to estimate from the ruminoreticulum was also addressed by Okine and Mathison (unpublished) who used chromium-mordanted fiber as the particulate marker. They found a significant relationship between fractional ruminoreticular clearance

rate (Y) and rate of passage through the gastrointestinal tract as determined from fecal material (X) of Y=0.0057(X) + 0.0138 (R^2=0.49; N=16; P=0.006; S.E.=0.0018). These results suggest that measurements of fecal passage rate can be used to predict ruminal passage rates although there may be considerable variability in the relationship. Aitchison et al. (1986), however, criticized rumen sampling for determining the rate of passage of particulate markers since difficulties are often encountered in obtaining representative samples of rumen digest which may result in less reliable estimates of rumen outflow rate. The authors suggested that these problems may be alleviated by sampling from the feces where thorough mixing is easier.

Particulate passage rate varied ($P<0.05$) from 0.022 to 0.037 h^{-1} for feeds fed at the low level and from 0.025 to 0.042 h^{-1} for feeds given at the higher intake level (Table 2.3). It is of interest to note that the values obtained in this experiment were only slightly lower than the mean rumen solid passage rates of 0.036 h^{-1} (61 observations with intakes ranging from 5.9 to 35.0 g Kg^{-1} b[illegible] weight) reported by Evans (1981a). In general the lower quality feeds had a slower rate of particulate passage (Table 2.3). It has been well established that clearance of feed residues from the ruminoreticulum by breakdown and passage is one of the major processes controlling both intake and the extent of digestion of forages (Ulyatt et al. 1986). It is also generally accepted that the amount of material in the ruminoreticulum is higher when low quality forages are fed (Grovum 1984). Thus, when intake is held constant, a poorer quality roughage would be expected to result in a slower rate of passage of particles

through the digestive tract.

It has been documented that as the level of intake increases with the same diet there is a corresponding increase in the rate of passage (Owens et al 1979; Grovum 1984). In this experiment, however, significant increases in rate of passage of particulate material with intake were only observed for the 75/25 hay diet (Table 2.4). This may have been because there were no other cases in which the target intake of two times maintenance was reached at the higher feeding level. Also, Van Soest (1982) has stated that the rumen distension factor can possibly counterbalance any tendency for increases in rate of passage with increased intake.

Rumen fluid dilution rates were higher than particulate passage rates (Table 2.3). It is generally accepted that the volume of water entering the rumen via animal ingestion is greater than the intake of solids and, due also to the addition of salivary secretions during the mastication process, the liquid phase usually travels at a faster rate through the digestive tract than the particulate phase (Evans 1981b). In this experiment the higher quality forages (hays and silages) had a faster rate of passage of the fluid fraction than did the straws at the low feeding level however the quality of forage did not have any significant effect on the passage of fluid through the digestive tract at the highest level of intake. Bosch et al. (1988) found that alfalfa silage had a significantly slower rate of fluid passage than did grass silage. This may be because less chewing activity was required with the alfalfa diet. Evans (1981b) reported that increasing digestible energy concentrations in the diet had

negative impacts on liquid turnover rates with sheep and cattle and suggested that salivary secretions may account for a large proportion of the fluid leaving the rumen with low energy, forage based diets.

No differences in fluid rate of passage were detected with increases in intake, with the exception of the 65/35 hay. These results are in agreement with Hodgson et al. (1976) who found no significant differences in liquid rates in sheep given three amounts of a grain-hay ration. Bull et al. (1979), however reported an increase in rumen liquid turnover rate from 0.034 at maintenance level of intake to 0.053 at two times maintenance level of intake. Also Grovum and Williams (1977) reported that liquid flow rate increases as intake increases. It is evident that more research is required in order to determine the effects of intake on rumen liquid rate of passage.

2.4.2 Feed fractions

The rapidly soluble fraction (A) of forages corresponds with the material which is expected to be almost completely degraded in the ruminoreticulum and rapidly available to rumen microorganisms. It is difficult to accurately measure fraction A, however, since estimates usually include any losses of material from the bag which causes an over-estimation of the soluble fraction (Varvikko and Lindberg 1985). The percentage of DM in fraction A ranged from 6.2 - 33.0% with wheat straw having the lowest values and the silages having the highest (Table 2.5). The extremely high negative correlations of fraction A DM with feed ADF and NDF (Table 2.7) are

in agreement with relationships reported in the literature (Seoane 1982; Nocek and Grant 1987) and are expected since NDF is not soluble (Nocek and Grant 1987). The observation that there were larger A fractions in hays and silages than in straw or prairie hay can be compared with results of Nocek and Grant (1987) who reported that DM disappearance from polyester bags after washing averaged 10-15 % higher for alfalfas than grasses. Lancaster and Patterson (1988) also reported values similar to the ones obtained in this experiment: straw lost the lowest amount of soluble DM (4%) and alfalfa hay the highest amount (19%) when forages were soaked in water for 1 h. These authors suggested fraction A represented the total amount of nonstructural material and its relative availability.

The percentage of CP from the silages which was soluble was significantly higher than that observed in the other feedstuffs with the exception of the treated wheat straw (Table 2.5). This is related to the ensiling process which has been shown to greatly affect the protein solubility of feedstuffs (McDonald and Wittenbury 1973; Demarquilly and Jarrige 1982). The relatively large proportion of CP in fraction A in the treated wheat straw was not unexpected since the slow-release supplement contained a high percentage of soluble nitrogen.

The three straw forages and the two silages had a lower percentage CP in fraction B which was explained by the low initial CP content in the straws and the high degree of CP solubility in the silages (Table 2.5). The percentage of feed CP in fraction C was the only feed fraction which could be predicted with a high degree of

accuracy in this experiment. Although the percentage of CP in this fraction was linearly related to CP, NDF and ADF, significant improvements in the relationship were noted between feed NDF and CP and fraction C CP when a quadratic relationship was used (Table 2.7). The prediction of fraction C CP from quadratic relationships (Fig. 2.1) has not been previously described in the literature to our knowledge. There was a significant negative relationship between fraction C CP in feed DM (Table 2.8) and the protein content of the DM (Table 2.1). This is in contrast with the positive correlation expected between feed CP and apparently indigestible CP in the animal as predicted by equations developed by the National Academy of Sciences - National Research Council (1984). It thus appears that nylon bag digestibility values might be more closely related to true digestibility rather than to apparent digestibility.

2.4.3 Prediction of intake

Very little information is available in the literature concerning the prediction of intake and digestibility using the in situ bag technique. Ørskov et al. (1988), who were quite positive about the potential of the procedure for this purpose, thus stated that more research is required in order to see how wide a range of forages their results with this technique can encompass.

Voluntary DM intake could be predicted reasonably well (r^2 = 0.71-0.85) from any of the CP, NDF or ADF content of the feeds. The use results from single in situ incubation times resulted in coefficient of determination values for prediction of intake (Table

2.8), which were similar (R^2=0.67-0.86) to those obtained using the chemical feed components in the prediction equations. This suggests that there was little advantage in using in situ data for predicting voluntary intake Through examination of data of Hovell et al. (1986) and Ørskov et al. (1988), similar conclusions can be drawn. Hovell et al. (1986) found that the in situ bag information explained 0.98 (A + B) and 0.98 ((A + B) + Kd) of the variation in intake whereas it can be calculated from their data that 0.35, 0.75 and 0.94 of the variability was explained by the CP, NDF and ADF contents of the feed, respectively. In the case of Ørskov et al. (1988) it can also be calculated that 0.50, 0.62 and 0.93 of the variability in intake was explained by the CP, NDF and ADF content of the feed whereas only 0.69 (A + B) to 0.79 ((A + B) + Kd) of the variation in intake was explained by the in situ bag procedure. It thus appears that both of these groups of researchers were overly optimistic about the potential of the in situ bag technique for predicting intake. In the only other comparisons which was found Chenost et al. (1970) found a significant relationship (R^2=0.67) between intake and 12-h incubation data. This was lower than the relationship (R^2=0.72) observed in this experiment.

For prediction equations to be useful, however, there must be potential for applying them to other data sets. The relationship between fraction (A + B) and voluntary DM intake (kg d^{-1}) resulted in a coefficient of determination of 0.69 (Appendix A; Table 2). However, predicted DM intakes for wheat straw, 75/25 hay and 37%DM silage were 3.29, 7.48 and 10.75 Kg d^{-1} whereas actual intakes were

3.8, 11.0 and 10.9 Kg d^{-1}, respectively. Use of coefficients developed by Ørskov et al. (1988) in the equation ((A + B) + Kd) resulted in predicted intakes of 3.81, 6.32 and 6.32 for wheat straw, 75/25 hay and 37% DM silage, respectively, indicating that the Ørskov et al. (1988) equations underestimated intakes for the better quality forages. It also should be emphasized that although the equations of Ørskov et al. (1988) gave a reasonable prediction of mean daily intake in this experiment this was because the animals used in both experiments were similar in live weight. Equations for describing intake based upon in situ or other techniques should be given in terms of g $kg^{-0.75}$ or kg intake per 100 kg body weight thereby allowing for the animal factor to be considered as well as the feed factor.

There appears to be potential for predicting voluntary intake from the particulate rate of passage (R^2=0.90) (Fig. 2.4). However, the relationship was only slightly better than that obtained when using chemical components and since rate of passage studies require a great deal of work (Pond et al. 1987), the use of rate of particulate passage in prediction equations cannot be justified. There was little value of including rates of digestion or passage along with chemical components in the prediction equations estimating voluntary intake (Table 2.9), although rate of passage appeared to give slightly better results than rates of digestion. This may be a result of including the straws in the regression relationships since these poor quality forages have limited amounts of material which can be degraded. Ørskov et al. (1988) could

not determine whether the rate constants of degradation of long to small particles were similar for all straws or if the rate constants associated with the physical breakdown were higher than the outflow rate constants and therefore not hindering intake.

2.4.4 Prediction of apparent digestibility

It has been well established that digestibility of forages varies considerably, not only between species of forages but also within one species (Aerts et al. 1977), thus there is a need for accurate methods of predicting forage digestibility. As in the case of intake the use of single in situ incubation data gave the best predictions (R^2=0.71-0.92) of apparent DM digestibility (Table 2.10), even though it is well known that digestibility in vivo is the product of retention time in the rumen and the degradation characteristics of the roughage concerned (Hovell et al. 1986). Chenost et al. (1970) reported that 12-h DM residue gave a correlation coefficient of 0.62 when used to predict DM digestibility. There seemed to be no major difference in accuracy of predictions from different incubation times although the 120-h incubation gave the lowest coefficient of determination (R^2=0.71). Chenost et al. (1970) reported that 48-h in situ incubation data best described in vivo OM digestibility (R^2=0.53 for 54 samples). Bittante et al. (1988) also stated that the 48-h single in situ incubation appeared to be the most effective method for prediction of OM digestibility. In practical terms either a 24 or 48 h incubation time would be recommended because 12 or 36 h incubation times would

be hard to schedule.

The use of chemical components of feeds explained almost as much of the variability encountered in DM digestibility as did the use of results from in situ incubations (Table 2.10). This is in contrast to the theoretical considerations of Mertens (1987) who criticized the simple linear models which included only the feed components since they failed to include the dynamic parameter associated with rates of passage and digestion.

Prediction of DM digestibility from the particulate rate of passage (Fig. 2.7) worked with slightly lower accuracy (R^2=0.72) than the use of chemical components or single in situ incubation times. At lower digestibilities there was a linear increase in rate of particulate passage with DM digestibility whereas in the case of the better quality feeds there was not a corresponding increase in particulate rate of passage (Fig. 2.7).

Waldo et al. (1972) predicted DM digestibility according to the equation: Digestibility = Fraction A + (B*KdB)/(KdB + KpB) where the two rate constants, rate of degradation (Kd) and rate of passage (Kp), are applied to the slowly degrading fraction (B). Application of this equation to results in this experiment resulted in slightly lower predicted than actual values for DM apparent digestibility, which may be expected since the in situ values only reflect rumen conditions whereas actual in vivo apparent digestibility is a result of digestion in the entire digestive tract. It has been well established that a significant amount of digestion does occur post-ruminally (Merchen 1988).

2.4.5 Use of rates of passage in prediction equations

Traditionally when the extent of degradation of feed components is estimated using the nylon bag technique the rate of passage has been estimated. However, it has been shown that an increase in outflow rate from the rumen from 2.2 to 6.6 % h^{-1} resulted in decreases in the effective degradability for fishmeal, soybean meal and cottonseed meal by 20, 18, and 14 %, respectively (Kristensen et al. 1982). These authors also reported that soybean meal and canola meal only obtained similar degradation characteristics with an outflow rate of 4.4% h^{-1}. Thus it is evident that the rate of passage can have a dramatic effect on the extent of ruminal degradation. There is however little information in the literature in which rates of passage have been measured and related to in situ incubations for prediction of intake or digestibility.

Although the use of the rate of particulate passage did result in a significant quadratic relationship with DM digestibility (Fig. 2.7), the inclusion of the rate constants in the prediction equations for estimating digestibility did not increase the predictive capabilities of the in situ technique over that obtained with the chemical feed components. This observation may be related to observations of Hovell et al. (1986) who discussed a two-fold problem when attempting to equate degradation characteristics with in vivo digestibility: firstly, different retention times in the rumen are required to obtain the same extent of degradation by different types of forages, and secondly, increasing the retention time can

theoretically improve the digestibility of some forages but will have no effect on other forages. Hovell et al. (1986) concluded that these two points stress the difficulty of equating specific in situ degradation results with in vivo apparent digestibility.

In order to further evaluate the importance of the rate of passage the data obtained from this experiment was used to predict DM apparent digestibility using the Waldo et al (1972) equation given above. Firstly, the predicted values were obtained using the rates of passage obtained using Cr-mordanted fiber and secondly, the same equation was used but the fractional rate of passage was held constant at 0.05 h^{-1}, a commonly assumed value (Stern and Satter 1983). The prediction of DM digestibility using the 0.05 h^{-1} value resulted in the equation: Digestibility = 0.73(x) + 20.01 (R^2=0.47). Although the regression was significant, the coefficient of determination was considerably lower than when the actual values for rates of passage were used (R^2 = 0.81). Consequently, it is apparent that the rate of passage can have a significant effect on digestibility of forages.

2.4.6 Conclusions

It is clear from the results of this experiment that the usefulness of the in situ bag procedure in estimating the voluntary intake and apparent digestibility of feedstuffs is limited. The use of single incubation times to predict voluntary DM intake and DM apparent digestibility did give adequate estimates, however, the resulting coefficients of determination were only slightly better

than those obtained when using chemical feed components. Moreover, Playne et al. (1978) indicated that 27 bags per incubation were required in order to ensure a probability of 90% of detecting a 5% difference in DM digestion between treatments. Mathison et al. (1988) found that 18 bags for each individual incubation time were required to obtain a reasonable confidence interval of 0.04 (P=0.05) for the estimation of bromegrass DM digestibility in the rumen. In this experiment 15 bags would have been required to predict 24 h DM digestibility at this level of precision. Thus although from a theoretical point of view there would be real value in including rates of passage in prediction equations for estimating digestibility, in this experiment the improvement in precision over that obtained using only the NDF content of the feed was not enough to warrant the time and expense involved.

2.5 REFERENCES

Aerts. J. V., De Brabander, D. L., Cottyn, B. C. and Buysse, F. X. 1977. Comparison of laboratory methods for predicting the organic matter digestibility of forages. Anim. Feed Sci. Technol. 2:337-349.

Aitchison, E. M., Gill, M., Dhanoa, M. S. and Osbourn, D. F. 1986. The effect of digestibility and forage species on the removal of digesta from the rumen and the voluntary intake of hay by sheep. Brit. J. Nutr. 56:463-476.

Association of Official Analytical Chemists. 1980. Official methods of analysis. 13th ed. AOAC, Washington, D. C.

Bae, D. H., Welch, J. G. and Smith, A. M. 1981. Forage intake and rumination by sheep. J. Anim. Sci. 49:1292-1299.

Bittante, G., Ramanzin, M., Cozzi, G. and Spanghero, M. 1988. Estimation of the organic matter in vivo digestibility and of the metabolizable energy content of feedstuffs and byproducts by means of the fiber bag technique. J. Anim. Sci. (Suppl) 66:495.

Bosch, M. W., Janssen, I. M., van Bruchem, J., Boer, H. and Hof, G. 1988. Digestion of alfalfa and grass silages in sheep. 1. Rates of fermentation in and passage from the reticulorumen. Netherlands J. of Agric. Sci. 36:175-185.

Bull, L. S., Rumpler, W. V., Sweeney, T. F. and Zinn, R. A. 1979. Influence of ruminal turnover on site of digestion. Fed. Proc. 38:2713-2719.

Chenost, M., Grenet, E., Demarquilly, C. and Jarrige, R. 1970. The use of the nylon bag technique for the study of forage digestion in the rumen and for predicting feed value. Proceedings of the 11th International Grassland Congress. Surfers Paradise, pp 697-710. University of Queensland Press St. Lucia, Australia.

Colucci, P. E., Chase, L. E. and Van Soest, P. J. 1982. Feed intake, apparent diet digestibility, and rate of particulate passage in dairy cattle. J. Dairy Sci. 65:1445-

Cote, M., Seoane, J. R., Gervais, R. E. and McQueen, R. E. 1982. Etudes sur la biodegradation de la matiere seche des fourrages par les methodes in vitro et des sacs de nylon. [Studies on the biodegradation of forage dry matter by in vitro mthods and nylon sacks.] Can. J. Plant Sci. 62:407-413.

de Boer, G., Murphy, J. J. and Kennelly, J. J. 1987. A modified method for determination of in situ rumen degradation of feedstuffs. Can. J. Anim. Sci. 67:93-102.

Demarquilly, C. and Jarrige, R. 1982. Assessment of the protein value of forages and its expression inn the new protein feeding systems. In Forage Protein Conservation and Utilization. Commission of the European Communities pp 147-172.

Dixon, R. M., Kennedy, P. M. and Milligan, L. P. 1983. Measurment of volume and flow in the digestive tract. In Nuclear Techniques for Assessing and Improving Ruminant Feeds. pp. 25-41. International Atomic Energy Agency, Vienna, Austria.

Ellis, W. C., Matis, J. H., Pond, K. R. Lascano, C. E. and Telford, J. p. 1983. Dietary influences on flow rate and digestive capacity. (F. M. C. Gilchrist and R. I. Mackie ed.) pages 269-293, Pretoria, Republic of South Africa, The Science Press.

Evans, E. 1981a. An evaluation of the relationships between dietary parameters and rumen liquid turnover rate. Can. J. Anim. Sci. 61:91-96.

Evans, E. 1981b. An evaluation of the relationships between dietary parameters and rumen solid turnover rate. Can J. Anim. Sci. 61:97-103.

Faichney, G. J. 1980. The use of markers to measure digesta flow from the stomach of sheep fed once daily. J. Agric. Sci. Camb. 94:313-318.

Figroid, G. J. and Griffiths, D. A. 1978. Behaviour of solute and particulate markers in the stomach of sheep given a concentrate diet. Br. J. Nutr. 40:71-82.

Goering, H. K. and Van Soest, P. J. 1970. Forage fiber analysis (apparatus, reagents, procedures and some applications). Handbook No. 379. ARS-USDA, Washington, D. C.

Goering, H. K., Gordon, C. H., Hemken, R. W., Waldo, D. R., Van Soest, P. J. and Smith, L. W. 1972. Analytical estimates of nitrogen digestibility in heat damaged forages. J. Dairy Sci. 55:1275-1280.

Grovum, W. L. 1984. Integration of digestion and digesta kinetics with control of feed intake - a physiological framework for a

model of rumen function. In Herbivore nutrition of the subtropics and tropics. (eds F.M.C. Gilchrist and R.I. Mackie), Pretoria, Republic of South Africa.

Grovum, W. L. and Williams, V. J. 1977. Rate of passage of digesta in sheep. 6. The effect of level of food intake on mathematical predictions of the kinetics of digesta in the reticulo-rumen and intestines. Br. J. Nutr. 38:425-436.

Hodgson, J. C., Thomas, P. C. and Wilson, A. G. 1976. The influence of the level of feeding on fermentation in the ruen of sheep receiving a diet of ground barley, ground hay and flaked maize. J. Agric. Sci. 87:297-302.

Hovell, F. D. DeB. 1985. Thoughts on roughage digestion by ruminants. The Rowett Institute Annual Report. 40:25-33.

Hovell, F. D. DeB., Ngambi, J. W. W., Barber, W. P. and Kyle, D. J. 1986. The voluntary intake of hay by sheep in relation to its degradability in the rumen as measured in nylon bags. Anim. Prod. 42:111-118.

Kempton, T. J. 1980. The use of nylon bags to characterise the potential degradability of feeds for ruminants. Trop. Anim. Prod. 5:107-116.

Kristensen, E. S., Moller, P. D. and Hvelplund, T. 1982. Estimation of the effective protein degradability in the rumen of cows using the nylon bag technique combined with the outflow rate. Acta. Agric. Scand. 32:123-127.

Lancaster, C. M. and Patterson, J. A. 1988. Effect of forage sterilization method on rate and extent of fiber degradation

by ruminal bacteria. J. Anim. Sci. 66:1800-1806.

Lucas, H. L. and Smart, W. W. G. 1959. Chemical composition and digestibility of forages. 16th Southern Pasture and Forage Crop Improvement Conference. pp. 23-26.

Mathison, G. W. 1974. Voluntary intake of oat straw by beef cows. Pages 12-13. In Fifty-third Annual Feeders' Day Report. Department of Animal Science, University of Alberta, Edmonton, Alberta.

Mathison, G. W., Milligan, L. P. and Weisenburger, R. D. 1984. Ruminant feed evaluation unit. pp 44-47 in 63rd Annual Feeders' Day Report. Department of Animal Science, University of Alberta, Edmonton, Alberta.

Mathison, G. W., Jahn, H. G., Walton, P. D. and Milligan, L. P. 1988. Use of the is situ technique in the study of degradation of lucerne and smooth bromegrass genotypes. Grass and Forage Sci. 43:474-481.

McDonald, P. and Wittenbury, R. 1973. The ensilage process. In Chemistry and Biochemistry of Herbages. (ed. G. W. Butler and R. W. Bailey) Vol. 3. Academic Press Inc., London.

Merchen, N. R. 1988. Digestion, absorption and excretion in ruminants. In The Ruminant Animal Digestive Physiology and Nutrition. Ed. D. C. Church. pp 172-201. A Reston Book, Prentice Hall, New Jersey.

Mertens, D. R. 1987. Predicting intake and digestibility using mathematical models of ruminal function. J. Anim. Sci. 64:1548-1558.

Mertens, D. R. and Ely, 1979. A dynamic model of fiber digestion and passage in the ruminant for evaluating forage quality. J. Anim. Sci. 49:1085-1095.

Mertens, D. R. and Loften, J. R. 1980. The effect of starch on forage fiber digestion dinetics in vitro. J. Dairy Sci.63:1437-1446.

Mehrez, A. Z. and Ørskov, E. R. 1977. A study of the artificial bag technique for determining the digestibility of feeds in the rumen. J. Agric. Sci. (Camb.) 88:645-650.

National Research Council, 1984. Nutrient requirements of beef cattle. 6th ed. National Academy Press, Washington, D.C.

Nocek, J. E. 1985. Evaluation of specific variables affecting in situ estimates of ruminal dry matter and protein digestion. J. Anim. Sci. 60:1347-1358.

Nocek, J. E. and Grant, A. L. 1987. Characterization of in situ nitrogen contamination of hay crop forages preserved at different dry matter percentages. J. Anim. Sci. 64:552-564.

Ørskov, E. R. and McDonald, I. M. 1979. The estimation of protein degradability int he rumen from incubation measurements weighted according to passage. J. Agric. Sci. (Camb.) 92:499-503.

Ørskov, E. R., Reid, G. W. and Kay, M. 1988. Predicition of intake by cattle from degradation characteristics of roughages. Anim. Prod. 46:29-34.

Owens, F. N., Kazemi, M., Galyean, M. L., Mizwicki, K. L. and Solaiman, S. G. 1979. Ruminal turnover rate - influence of

feed additives, feed intake and roughage level. Okla. Agric. Exp. Sta. Rep. MP-104. pp. 27-29.

Playne, M. J., Khumnualthong, W. and Echeuarria, M. G. 1978. Factors affecting the digestion of oesophageal fistula samples and hay samples in nylon bags in the rumen of cattle. J. Agric. Sci. (Camb.) 90:193-204.

Pond, K. R., Burns, J. C. and Fisher, D. H. 1987. External markers - use and methodology in grazing studies. pp 49-53. Proceedings, Grazing Livestock Nutrition Conference, Jackson, Wyoming, U.S.A.

Poppi, B. P., Norton, B. W., Minson, D. J. and Hendricksen, R. E. 1980. The validity of the critical size theory for particles leaving the rumen. J. Agric. Sci. (Camb.) 94:275-280.

Schneider, B. H. and Flatt, W. P. 1975. The evaluation of feeds through digestibility experiments. The University of Georgia Press, Athens, Georgia.

Seoane, J. R. 1982. Relationships between the physiochemical characteristics of hays and their nutritive value. J. Anim. Sci. 55:422-431.

Steel, R. G. D. and Torrie, J. H. 1980. Principles and procedures of statistics - A biometrical approach. McGraw-Hill Book Company.

Stern, M. D., Ortega, M. E. and Satter, L. D. 1983. Retention time in the rumen and degradation of protein supplements fed to lactating dairy cattle. J. Dairy Sci. 66:1264-1271.

Uden, P., Colucci, P. E. and Van Soest, P. J. 1980. Investigations

of chromium, cerium, and cobalt as markers in digesta. Rate of passage studies. J. Sci. Food Agric. 31:625-632.

Ulyatt, M. J., Dellow, D. W., John, A., Reid, C. S. W. and Waghorn, G. C. 1986. Contribution of chewing during eating and rumination to the clearance of digesta from the ruminoreticulum. pages 498-530 (ed L. P. Milligan, W. L. Grovum, and A. Dobson) In Control of Digestion and Metabolism in Ruminants. Proceedings of the Sixth International Symposium on Ruminant Physiology held at Banff, Canada. A Reston Book.

Van Soest, P. J. 1982. Nutritional Ecology of the Ruminant. O & B Books, Corvallis, Oregon.

Van Soest, P. J. 1967. Development of a comprehensive system of feed analysis and its application to forages. J. Anim. Sci. 26:119-128.

Varvikko, T. and Lindberg, J. E. 1985. Estimation of microbial nitrogen in nylon-bag residues by feed 15N dilution. Brit. J. Nutr. 54:473-481.

Waldo, D. R., Smith, L. W. and Cox, E. L. 1972. Model of cellulose disappearance from the rumen. J. Dairy Sci. 55:125-129.

Winer, B. J. 1971. Statistical principles in experimental design. Second Edition. McGraw Hill.

Table 2.1. Composition of feed dry matter used for in situ incubation

	Straw			Prairie	Hay			Silage	
	Wheat	Wheat+Supp	Barley	Hay	75/25†	65/35†	50/50†	28% DM	37% DM
Dry matter (%)	91.1	93.7	88.9	92.9	90.4	88.6	90.8	28.4	37.1
Crude protein (%)	4.3	6.5	4.0	5.8	13.0	15.3	13.1	10.7	13.4
Neutral detergent fiber (%)	82.1	76.3	83.8	70.1	50.3	44.2	57.7	59.4	54.6
Acid detergent fiber (%)	48.0	44.8	51.0	37.4	31.9	30.5	33.9	40.6	38.5
Lignin (%)	7.8	7.5	7.5	6.8	6.5	6.1	6.7	7.9	7.0
Calcium (%)	0.12	0.23	0.32	0.41	1.62	2.36	1.72	1.61	1.43
Phosphorus (%)	0.05	0.15	0.19	0.11	0.18	0.18	0.16	0.26	0.23
Ash (%)	5.9	8.1	5.9	12.1	9.6	11.5	12.3	10.8	9.9
ADIN‡ (%)	0.17	0.16	0.12	0.15	0.19	0.25	0.19	0.25	0.21

†Ratio of alfalfa to grass.

‡Acid detergent insoluble nitrogen.

Table 2.2. Animal weight and voluntary dry matter intake

	Straw†			Prairie	Hay			Silage		
	Wheat	Wheat+Supp	Barley	Hay	75/25‡	65/35‡	50/50‡	28% DM	37% DM	S.E.§
Weight (kg)	298.0d	306.0d	310.0d	304.0d	384.0b	377.0bc	359.0c	397.0b	429.0a	2.89
Intake of total dry matter intake										
kg 100kg^{-1} BW¶	1.56d	1.52d	1.19e	2.00c	2.85a	2.48b	2.77a	2.12c	2.60ab	0.112
Intake of forage dry matter										
kg d^{-1}	3.8g	3.9g	3.0g	6.1f	11.0a	9.4cd	9.9bc	8.5e	10.9ab	0.434
kg 100kg^{-1} BW¶	1.27e	1.27e	1.00f	2.00d	2.85a	2.48c	2.77ab	2.12d	2.60bc	0.106
g kg$^{-0.75}$	53.2e	52.7e	41.2f	83.0d	126.0a	110.0b	120.0a	95.0c	118.0ab	4.65

†Dry matter intake values have been corrected for barley grain (fed at the level of 15% of straw dry matter intake) and supplement (fed at the level of 11.5% of straw dry matter)

‡Ratio of alfalfa to grass.

§Five animals were used to determine each mean.

¶Body weight.

a-g Values in the same row not followed by the same letter differ significantly ($P<0.05$).

Table 2.3. The effect of forage type on the rate of passage of fluid and particulate matter and on the apparent digestibility of dry matter (DM), organic matter (OM), acid detergent fiber (ADF) and neutral detergent fiber (NDF) at the low and high level of intake

	Straw†			Native	Hay‡			Silage		
	Wheat	Wheat+Supp	Barley	Prairie	75/25‡	65/35‡	50/50‡	28% DM	37% DM	SE§
Low intake										
Dry matter intake¶ (g $Kg^{-0.75}$ d^{-1})	52.0d	56.0c	51.0d	54.8c	69.3ab	72.8a	67.5b	72.3a	66.0b	1.59
Rate of passage (fraction h^{-1})										
Particulate	0.023ab	0.022b	0.020b	0.025ab	0.028ab	0.034ab	0.035ab	0.025ab	0.037a	0.004
Fluid	0.046abc	0.043bc	0.040c	0.055ab	0.050abc	0.054ab	0.058ab	0.060a	0.055ab	0.005
Apparent digestiblity (%)										
DM	41.1d	36.8e	42.9cd	44.2c	63.4a	62.2a	58.2b	57.8b	63.7a	1.05
OM	43.0d	39.5e	32.0f	49.2c	66.2a	65.4a	61.2b	59.6b	65.2a	1.04
CP	49.6d	56.8c	36.2f	38.2e	70.9a	71.2a	63.3b	63.1b	63.3b	2.29
ADF	34.5de	32.0e	39.6cd	35.8de	51.9a	51.5a	41.8bc	45.4b	54.2a	2.31
NDF	40.6cd	37.4d	44.3c	43.6c	54.5a	55.7a	48.8b	49.9b	58.6a	2.06
High intake										
Dry matter intake (g $Kg^{-0.75}$ d^{-1})				78.3b	111.8a	103.8a	109.0a	89.8b	106.3a	2.75
Rate of passage (fraction h^{-1})										
Particulate				0.025c	0.036ab	0.031bc	0.035ab	0.032bc	0.042a	0.003
Fluid				0.061	0.049	0.045	0.059	0.056	0.060	0.005
Apparent digestibility (%)										
DM				43.9c	60.4b	58.9b	57.6b	59.1b	63.9a	1.15
OM				49.7c	62.8b	63.0b	60.3b	61.0b	65.8a	1.06
CP				29.5b	67.6a	67.1a	64.1a	63.6a	63.0a	1.54
ADF				35.8c	42.7b	46.4b	43.0b	45.5b	52.0a	1.62
NDF				44.2c	48.4b	51.1b	48.3b	50.3b	55.3a	1.41

†The dry matter and organic matter apparent digestibilities for the three straws have been corrected for nutrient contribution by the barley grain and liquid supplement addition.

‡Ratio of alfalfa to grass.

§Means are based upon four observations for rate of passage and five for digestibility measurements.

¶Intakes for wheat, wheat plus supplement and barley straw included 8.8, 8.8 and 9.2 g DM $Kg^{-0.75}$, daily, respectively, of grain and supplement at low level of intake.

a-f values in the same row not followed by the same letter differ significantly ($P<0.05$).

Table 2.4. Percentage of dry matter, neutral detergent fiber, and crude protein which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C), and rates of degradation (Kd) of slowly degradable fractions

	Straw			Prairie	Hay			Silage		
	Wheat	Wheat+Supp	Barley	Hay	75/25†	65/35†	50/50†	28% DM	37% DM	S.E.‡
Dry matter										
Fraction A	6.2e	9.7de	7.0e	12.5d	20.2c	27.4b	17.3c	29.6a	33.0a	1.81
Fraction B	38.3b	40.4b	43.0ab	53.8a	43.2ab	47.2ab	48.1ab	43.9ab	45.1ab	3.53
Fraction C	55.5a	50.0a	50.1a	33.7b	36.6b	25.4c	34.6b	26.6c	22.0c	2.61
Kd§	0.032a	0.024a	0.025a	0.030a	0.059b	0.055b	0.044a	0.030a	0.032a	0.006
Neutral detergent fiber¶										
Fraction B	42.6de	42.3de	46.7de	58.5bc	37.9e	51.5cd	48.8d	62.3b	71.8a	3.35
Fraction C	57.4ab	57.7ab	53.3ab	41.5cd	62.2a	48.5bc	51.2ab	37.8d	28.3e	3.35
Kd§	0.031	0.026	0.025	0.033	0.041	0.040	0.038	0.036	0.028	0.005
Crude protein										
Fraction A	11.9c	51.6a	13.2c	11.9c	27.4bc	23.6bc	34.4b	56.3a	64.2a	9.35
Fraction B	13.2b	2.2b	10.1b	48.0a	56.1a	61.3a	47.2a	23.0b	23.0b	8.04
Fraction C	75.0a	46.1b	76.7a	40.1b	16.6c	15.1c	18.4c	20.7c	12.9c	7.75
Kd§	0.008	0.006	0.044	0.028	0.033	0.114	0.041	0.057	0.010	0.030

†Ratio of alfalfa to grass.

‡Standard error of the mean is based upon three observations per mean.

§Fraction h^{-1}.

¶For neutral detergent fiber, fraction B was calculated as 100 - fraction C.

a-e Values in the same row not followed by the same letter differ significantly ($P<0.05$).

Table 2.5. Amount of neutral detergent fiber and crude protein which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C) expressed as a percentage of feed dry matter

	Straw			Prairie	Hay			Silage		
	Wheat	Wheat+Supp	Barley	Hay	75/25†	65/35†	50/50†	28% DM	37% DM	S.E.‡
Neutral detergent fiber§										
Fraction B	35.0bc	32.2c	39.2ab	41.0a	19.0e	22.8e	28.2d	37.0ab	39.2ab	1.80
Fraction C	47.2a	44.1a	44.6a	29.1b	31.3b	21.4c	29.6b	22.4c	15.4d	1.81
Crude protein										
Fraction A	0.5d	3.4c	0.5d	0.7d	3.6c	3.6c	4.5c	6.1b	8.6a	0.51
Fraction B	0.6d	0.2d	0.4d	2.8c	7.3b	9.4a	6.2b	2.5c	3.1c	0.61
Fraction C	3.3	3.0	3.1	2.3	2.2	2.3	2.4	2.2	1.7	0.46

†Ratio of alfalfa to grass.

‡Standard error of the mean is based upon three observations per mean.

§For neutral detergent fiber, fraction B was calculated as 100 - fraction C.

a-e Values in the same row not followed by the same letter differ significantly ($P<0.05$).

Table 2.6. Relationships between feed dry matter composition and percentage of dry matter (DM), crude protein (CP), and neutral detergent fiber (NDF) which was soluble (fraction A), slowly degradable (fraction B) and undegradable (fraction C)

Item	Equation†	R^2	S.E. Estimate	Probability
Dry matter‡				
Fraction A	1.55(feed %CP) + 0.6	0.91	2.58	0.000
	-0.48(feed %NDF) + 46.3	0.97	1.54	0.000
	-0.87(feed %ADF§) + 48.7	0.85	3.24	0.001
Fraction B	0.33(feed %CP) + 41.9	0.09	5.49	0.258
	-0.14(feed %NDF) + 53.8	0.17	5.25	0.183
	-0.36(feed %ADF) + 59.2	0.32	4.73	0.092
Fraction C	-2.21(feed %CP) + 58.3	0.65	7.64	0.004
	0.72(feed %NDF) - 8.9	0.72	6.84	0.002
	1.24(feed %ADF) - 12.0	0.54	8.77	0.012
Crude protein‡				
Fraction A	-0.19(feed %CP) + 37.6	0.04	15.70	0.328
	-0.34(feed %NDF) + 38.20	0.04	15.76	0.342
	-0.34(feed %ADF) + 38.20	0.04	15.76	0.342
Fraction B	-1.40(feed %CP) + 129.8	0.81	11.87	0.003
	-2.79(feed %NDF) + 144.7	0.88	9.37	0.001
	-2.79(feed %ADF) + 144.7	0.88	9.37	0.001
Fraction C	-5.38(feed %CP) + 87.2	0.86	10.11	0.000
	1.67(feed %NDF) - 71.9	0.88	9.25	0.000
	3.14(feed %ADF) - 88.7	0.78	12.82	0.001
	(-19.23*feed %CP) + (0.74*feed $\%CP^2$) + 139.0	0.96	6.08	0.000
	(-5.35*feed %NDF) + (0.05*feed $\%NDF^2$) + 147.2	0.98	3.71	0.000
	(-11.21*feed %ADF) + (0.18*feed $\%ADF^2$) + 192.0	0.86	10.98	0.006
Neutral detergent fiber‡				
Fraction C	-0.70(feed %CP) + 55.4	0.08	11.19	0.230
	0.22(feed %NDF) + 34.0	0.08	11.21	0.225
	0.12(feed %ADF) + 44.2	0.01	8.00	0.386

†Quadratic relationships only given when significant.

‡Regression relationships based upon nine feeds.

§Acid detergent fiber.

Table 2.7. Relationships between feed dry matter composition and amount of crude protein (CP) in fraction A (soluble), fraction B (slowly degradable) and fraction C (undegradable) and neutral detergent fiber (NDF) in fraction C expressed as a percentage of feed dry matter

Item	Equation	R^2	S.E. Estimate	Probability
Crude protein†				
Fraction A	0.10(feed %CP) + 9.6	0.02	11.88	0.382
	0.18(feed %NDF) + 8.7	0.02	11.88	0.383
	0.08(feed %ADF‡) + 6.5	0.01	6.94	0.412
Fraction B	-0.56(feed %CP) + 56.5	0.51	9.44	0.036
	-1.23(feed %NDF) + 68.5	0.68	7.56	0.011
	-0.80(feed %ADF) + 43.5	0.78	3.77	0.004
Fraction C	-0.09(feed %CP) + 3.3	0.62	0.62	0.006
	0.03(feed %NDF) + 0.06	0.69	0.30	0.003
	1.72(feed %ADF) - 52.6	0.82	6.12	0.000
Neutral detergent fiber†				
Fraction C	-2.08(feed %CP) + 51.6	0.65	7.15	0.004
	0.67(feed %NDF) - 11.2	0.71	6.55	0.002
	0.56(feed %ADF) - 2.8	0.63	3.28	0.005

†Regression relationship based upon nine feeds.

‡ADF is acid detergent fiber.

Table 2.8. Dry matter, neutral detergent fiber and crude protein residues (g g^{-1} incubated) at specific in situ incubation times

Time of Incubation (h)	Straw			Prairie Hay	Hay			Silage		S.E.‡
	Wheat	Wheat+Supp	Barley		75/25†	65/35†	50/50†	28% DM	37% DM	
Dry matter										
0	0.938a	0.904ab	0.930a	0.875bc	0.798d	0.728e	0.833cd	0.704e	0.670f	0.014
4	0.909a	0.868ab	0.906a	0.829b	0.729c	0.642d	0.763c	0.689d	0.615d	0.017
8	0.880a	0.838ab	0.872a	0.785b	0.665c	0.559de	0.697c	0.607d	0.530e	0.019
12	0.858a	0.800a	0.824a	0.732b	0.609c	0.474e	0.610c	0.551d	0.504de	0.018
24	0.796a	0.763a	0.736a	0.641b	0.481c	0.358d	0.483c	0.471c	0.405d	0.017
36	0.729a	0.706a	0.723a	0.537b	0.413c	0.305d	0.408c	0.417c	0.335d	0.020
48	0.682a	0.660a	0.656a	0.462b	0.410c	0.307d	0.398c	0.358cd	0.310d	0.018
72	0.591a	0.603a	0.581a	0.397b	0.371bc	0.258d	0.352c	0.341c	0.264d	0.012
96	0.575a	0.537b	0.537b	0.373c	0.349cd	0.314de	0.347cd	0.290e	0.238f	0.012
120	0.521a	0.500a	0.501a	0.337bc	0.366b	0.261d	0.323c	0.266d	0.220e	0.010
Neutral detergent fiber										
0	1.082b	1.020b	1.024b	1.095b	1.300a	1.331a	1.190ab	1.011b	0.988b	0.042
4	1.059b	1.069b	0.974b	1.056b	1.307a	1.164b	1.145b	0.956b	0.996b	0.044
8	1.019abc	1.042ab	1.004abc	1.004abc	1.113a	1.075ab	1.054ab	0.936bc	0.879c	0.034
12	0.994ab	0.986ab	0.934ab	0.919ab	1.076a	0.898ab	0.961ab	0.835b	0.817b	0.045
24	0.903a	0.921a	0.835ab	0.775bc	0.913a	0.753bc	0.778bc	0.712c	0.682c	0.025
36	0.782ab	0.872a	0.791ab	0.681bc	0.748abc	0.584d	0.631cd	0.624cd	0.542d	0.037
48	0.740ab	0.791a	0.715ab	0.573c	0.705ab	0.615bc	0.621bc	0.536c	0.507c	0.031
72	0.648ab	0.708a	0.645ab	0.443c	0.657ab	0.545abc	0.532bc	0.460c	0.418c	0.038
96	0.612a	0.622a	0.583ab	0.430c	0.648a	0.504b	0.542ab	0.385c	0.367c	0.025
120	0.552a	0.577a	0.533a	0.415b	0.622a	0.550a	0.512a	0.377bc	0.318c	0.024
Crude protein										
0	0.887a	0.485bc	0.862a	0.884a	0.724a	0.763a	0.655ab	0.439c	0.357c	0.051
4	0.752a	0.372c	0.723a	0.764a	0.486bc	0.634ab	0.533bc	0.404bc	0.309c	0.060
8	0.701a	0.461abc	0.695a	0.541ab	0.367bc	0.440abc	0.463abc	0.330bc	0.248c	0.060
12	0.508ab	0.373bc	0.667a	0.647a	0.281bc	0.319bc	0.345bc	0.265bc	0.170c	0.062
24	0.659a	0.429ab	0.689a	0.555a	0.214b	0.200b	0.245b	0.224b	0.213b	0.075
36	0.867a	0.423c	0.653b	0.479c	0.170d	0.139d	0.230d	0.214d	0.160d	0.050
48	0.793a	0.437b	0.698a	0.457b	0.140c	0.102c	0.171c	0.210c	0.134c	0.056
72	0.800a	0.408b	0.712a	0.469b	0.184c	0.132c	0.177c	0.164c	0.157c	0.062
96	0.825a	0.502b	0.682a	0.322c	0.136c	0.109c	0.189c	0.199c	0.162c	0.059
120	0.615ab	0.462bc	0.762a	0.403c	0.165d	0.177d	0.172d	0.208d	0.128d	0.048

†Ratio of alfalfa to grass.

‡Standard error of the mean based upon three observations.

a-f Values in the same row with different letters are significantly different ($P<0.05$).

Table 2.9. Prediction of voluntary dry matter intake

Equation†	R^2‡	S.E.	Probability
Chemical components of feed			
4.97 - 0.045(feed NDF)	0.85	0.293	0.002
5.84 - 0.091(feed ADF)	0.85	0.291	0.002
0.744 + 0.140(feed CP)	0.71	0.407	0.008
Single time incubations			
4.77 - 4.13(12 h DM residue)	0.72	0.400	0.006
4.20 - 3.79(24 h DM residue)	0.79	0.348	0.003
3.98 - 3.81(36 h DM residue)	0.86	0.287	0.002
3.97 - 4.09(48 h DM residue)	0.80	0.337	0.003
3.93 - 4.53(72 h DM residue)	0.79	0.344	0.003
4.02 - 5.00(96 h DM residue)	0.75	0.373	0.004
3.88 - 5.03(120 h DM residue)	0.67	0.433	0.009
Potentially degradable dry matter			
-0.871 + 0.048(A + B)	0.63	0.458	0.012
Rate of degradation			
0.530 + 41.07(Kd)	0.58	0.599	0.018
-1.19 + 0.035(A + B) + 28.5Kd	0.86	0.305	0.006
4.87+ 3.52(Kd) - 0.043(feed NDF)	0.85	0.314	0.007
5.85 - 2.16(Kd) - 0.094(feed ADF)	0.85	0.314	0.007
0.353 + 20.16(Kd) + 0.102(feed CP)	0.79	0.372	0.015
Rate of passage			
-0.606 + 95.65(Kp)	0.71	0.406	0.006
-10.39 + 805(Kp) - 12333(Kp^2)	0.90	0.258	0.002
-1.08 + 0.021(A + B) + 64.23(Kp)	0.77	0.393	0.020
3.35 + 31.94(Kp) - 0.034(feed NDF)	0.88	0.288	0.004
3.53 + 39.43(Kp) - 0.065(feed ADF)	0.90	0.252	0.002
0.034 + 50.58(Kp) + 0.073(feed CP)	0.74	0.411	0.024

†Abbreviations used in the equation are as follows: A is the percentage of dry matter which is soluble, B is the percentage of dry matter which is slowly degradable, Kd is the rate of digestion (% h^{-1}) of fraction B, and Kp is the rate of passage (% h^{-1}) of particulate matter measured the low level of intake.

‡Regression relationships based upon nine feeds.

Table 2.10. Predicition of apparent digestibility (%) of dry matter at the low feeding level

Equation†	R^2‡	S.E.	Probability
Chemical components of feed			
31.47 + 2.251(feed %CP)	0.77	5.50	0.004
97.29 - 0.701(feed %NDF)	0.86	4.35	0.002
98.76 - 1.174(feed %ADF)	0.60	7.29	0.010
Single time incubations			
98.34 - 69.55(12 h DM residue)	0.86	4.32	0.002
88.03 - 62.70(24 h DM residue)	0.92	3.35	0.001
82.59 - 59.67(36 h DM residue)	0.89	3.88	0.001
82.52 - 64.21(48 h DM residue)	0.83	4.72	0.002
81.88 - 70.92(72 h DM residue)	0.82	4.90	0.002
83.14 - 78.04(96 h DM residue)	0.78	5.46	0.004
81.35 - 78.43(120 h DM residue)	0.71	6.25	0.008
Potentially degradable dry matter			
5.61 + 0.742(A + B)	0.69	6.47	0.008
Rate of degradation			
30.06 + 603.5(Kd)	0.51	8.07	0.024
26.94 + 1.811(feed %CP) + 234(Kd)	0.82	5.29	0.010
99.34 - 0.718(feed %NDF) - 24.9(Kd)	0.86	4.70	0.006
79.64 - 0.877(feed %ADF) + 200.3(Kd)	0.62	7.70	0.065
1.28 + 0.581(A + B) + 392.6(Kd)	0.87	4.48	0.005
13.71 + 0.885(Predicted¶)	0.81	4.98	0.003
Rate of passage			
13.17 + 1412.9(Kp)	0.66	6.77	0.010
-75.14 + 7823(Kp) - 111338(Kp^2)	0.72	6.56	0.030
29.30 + 2.064(feed %CP) + 141.1(Kp)	0.77	5.93	0.018
81.72 - 0.592(feed %NDF) + 310.0(Kp)	0.87	4.52	0.005
50.20 - 0.584(feed %ADF) + 910.4(Kp)	0.72	6.57	0.030
3.22 + 0.451(A + B) + 747.9(Kp)	0.76	6.06	0.020
11.49 + 1041.0(Kp) + 325.1(Kd)	0.76	6.11	0.021

†Abbreviations used in the equations are as follows: A is the percentage of dry matter which is soluble, B is the percentage of dry matter which is slowly degradable, Kd is the rate of digestion (fraction h^{-1}) of fraction B, and Kp is the rate of passage (fraction h^{-1}) of particulate matter measured at low level of feeding, NDF refers to neutral detergent fiber, ADF refers to acid detergent fiber and CP refers to crude protein.

‡Regression relationships based upon nine feeds.

¶Predicted DM values determined using equation described by Waldo et al. (1972): DM digestibility=fraction A + (fraction B*Kd)/(Kd + Kp).

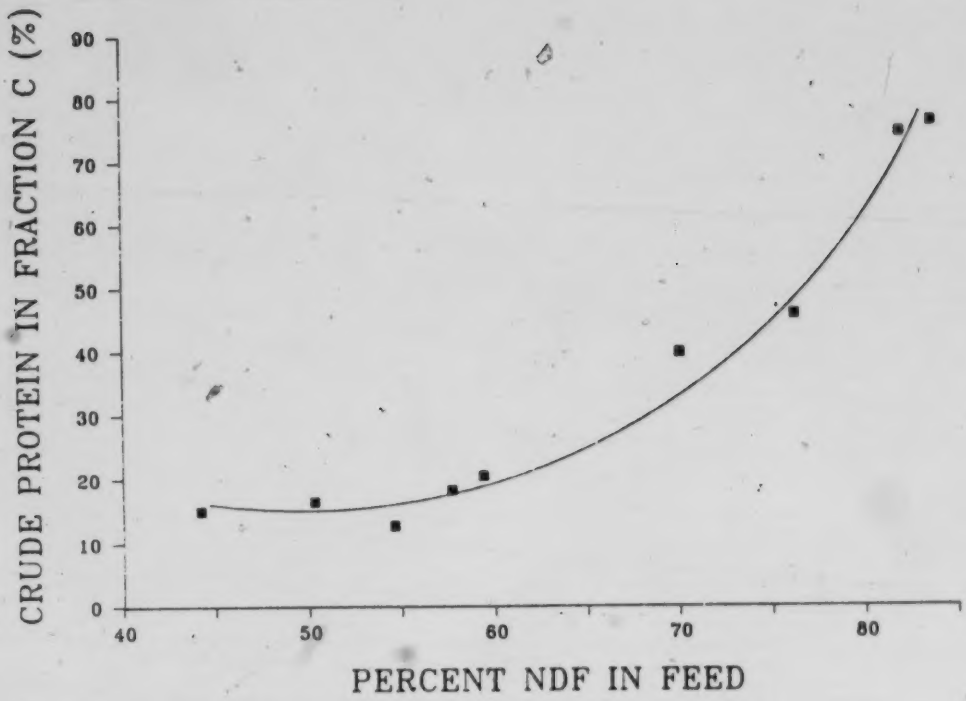

Fig. 2.1. Quadratic relationship between percent neutral detergent fiber (NDF) in feed and percent crude protein in fraction C (undegradable portion) (Y=-5.35*feed %NDF + 0.05*feed %NDF^2 + 147.2: n=9, R^2=0.98, S.E.=3.71.

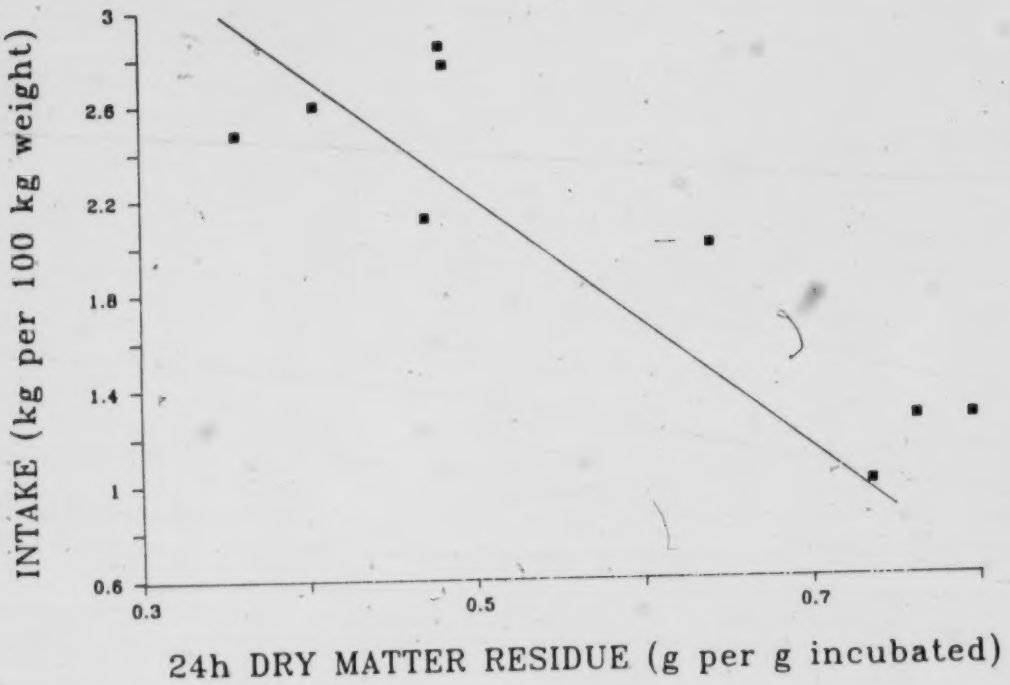

Fig. 2.2. Linear relationship between 24 hour in situ dry matter residue and voluntary dry matter intake (kg per 100 kg body weight) (Y=4.20 - 3.79*24 h dry matter residue: n=9, R^2=0.79, S.E.=0.346).

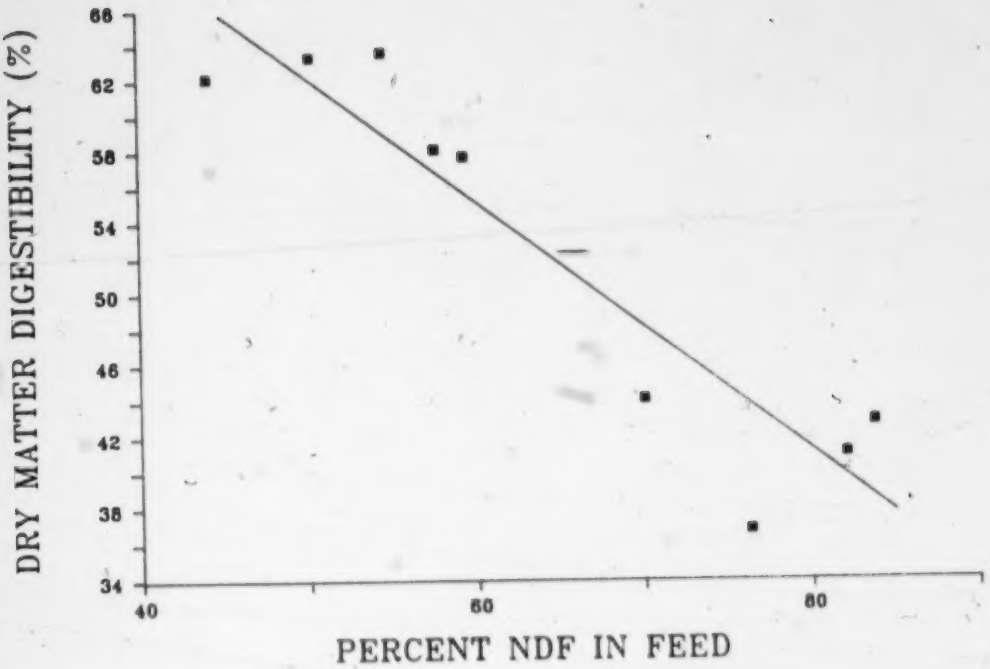

Fig. 2.3. Linear relationship between percent neutral detergent fiber (NDF) content of feeds and dry matter digestibility (%) (Y-97.29 - 0.701*feed %NDF: n-9, R^2-0.86, S.E.-4.35).

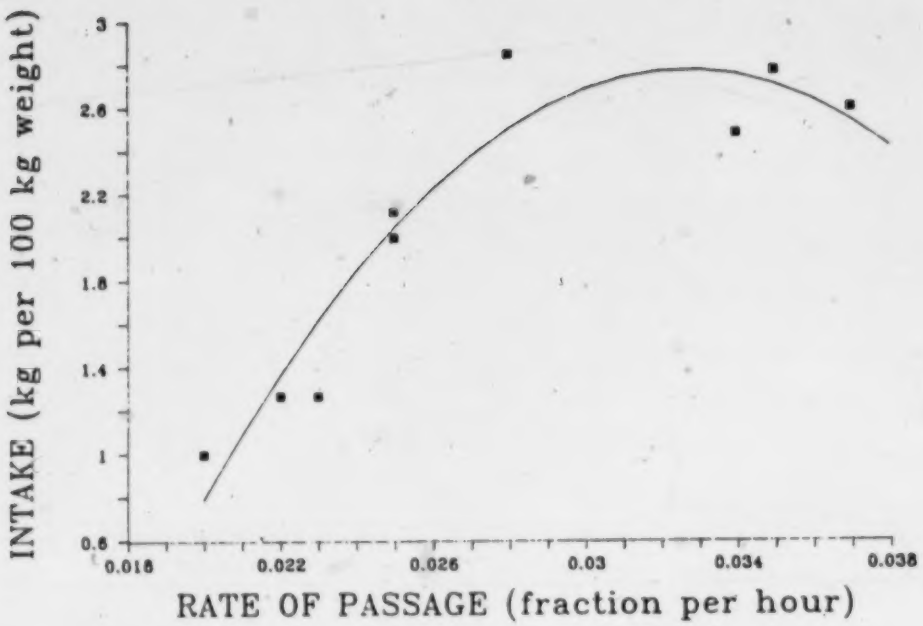

Fig. 2.4. Quadratic relationship between the rate of particulate passage (fraction h^{-1}) and voluntary dry matter intake (Y=-10.4 + 806*rate of passage - 12332*rate of passage^2: n=9, R^2=0.90, S.E.=0.253).

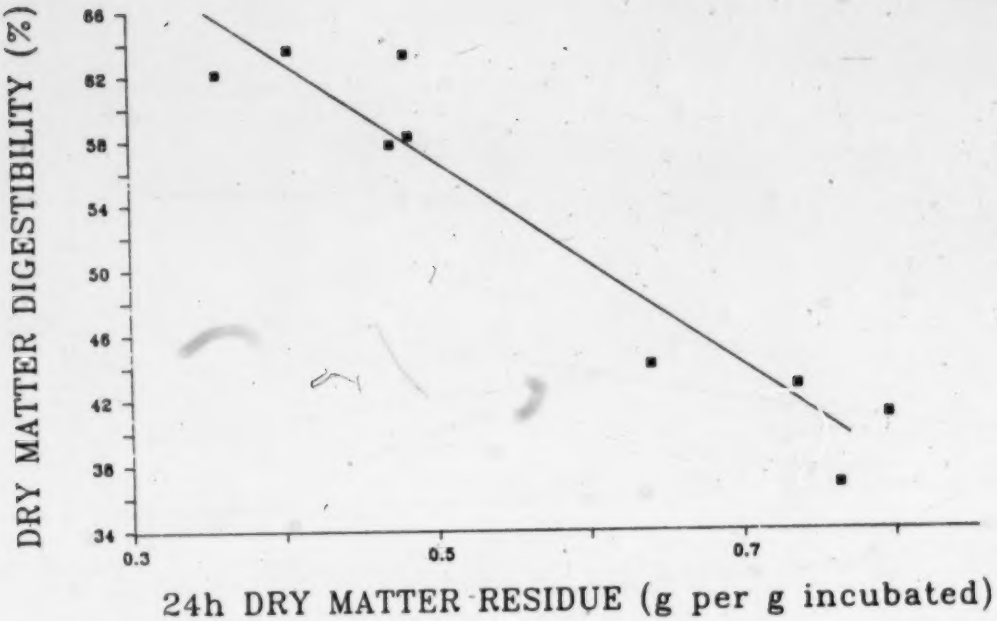

Fig. 2.5. Linear relationship between percent neutral detergent fiber (NDF) content of feeds and dry matter digestibility (%) (Y=97.29 - 0.701*feed %NDF: n=9, R^2=0.86, S.E.=4.35).

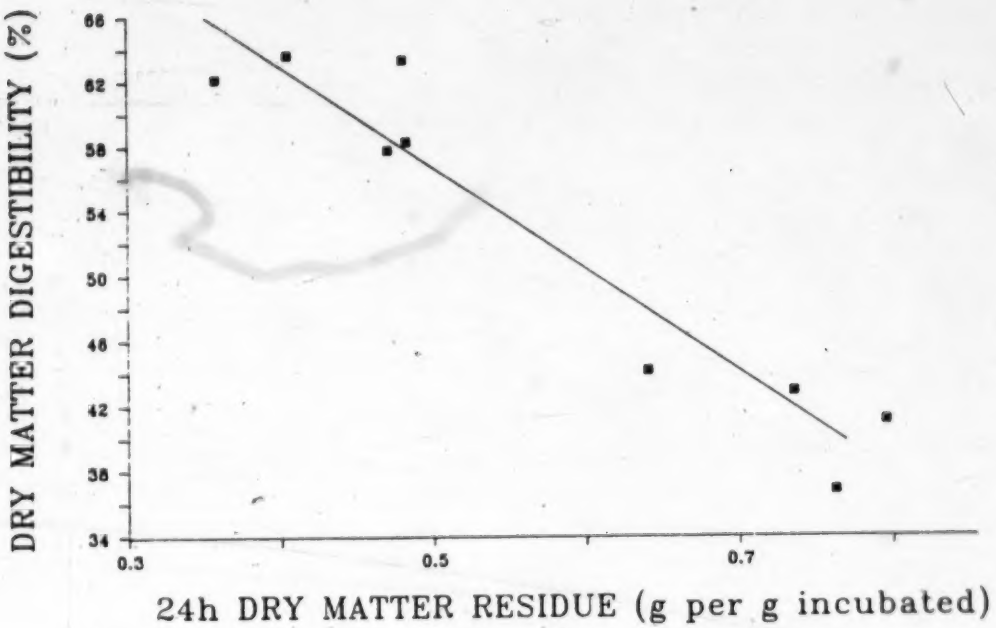

Fig. 2.6. Linear relationship between 24 hour in situ dry matter residue and dry matter digestibility (%) (Y=88.03 - 62.7*24 h dry matter residue: n=9, R^2=0.92, S.E.=3.35).

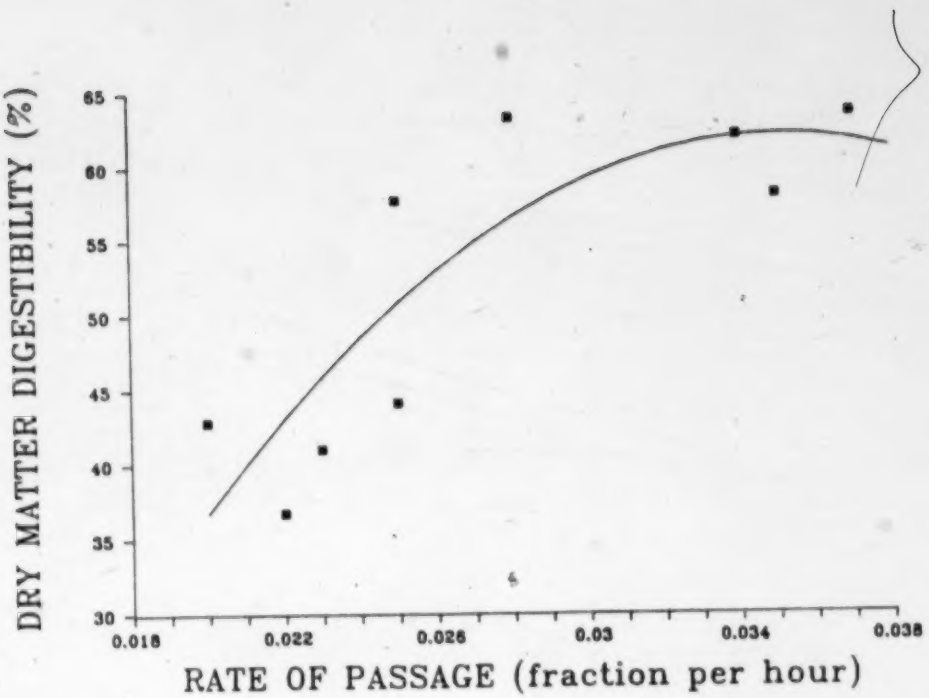

Fig. 2.7. Quadratic relationship between rate of particulate passage (fraction h^2) and dry matter digestibility (%) (Y=-75.14 + 7823*rate of passage - 111338*rate of passage^2: n=9, R^2=0.72, S.E.=6.56).

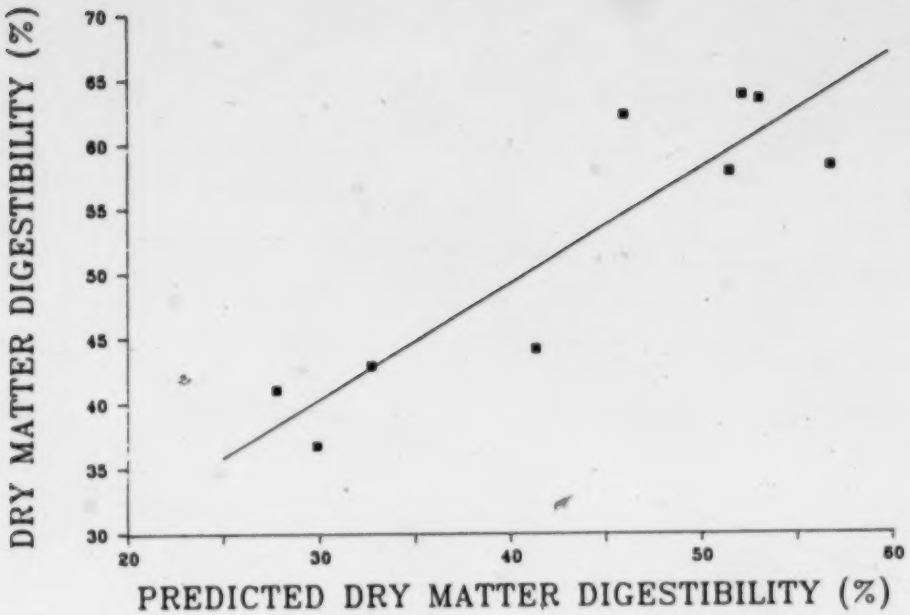

Fig. 2.8. Linear relationship between actual and predicted dry matter digestibility (%) calculated from the equation of Waldo et al. (1972): DM digestibility = fraction A + (fraction B*KdB)/(KdB + Kp) where DM=dry matter, B=slowly degradable fraction, Kd=rate of degradation of slowly degradable fraction and Kp is passage rate of particulate material (Y=13.76 + 0.885*Predicted: n=9, R^2=0.81, S.E.=4.98).

III GENERAL DISCUSSION

Considerable research has been conducted on the use of in situ bag technique in areas such as evaluating protein degradability in the rumen (Ørskov and McDonald 1979; Ganev et al. 1979; Kristensen et al. 1982; Stern and Satter 1984), determining protein availability in the whole animal (de Boer et al. 1987), predicting intake (Chensot et al. 1[illegible] Hovell et al. 1986; Ørskov et al. 1988) and predicting apparent digestibility (Chenost et al. 1970; Hovell et al. 1986). The main advantage of the technique is that the dynamic nature of digestion can be considered. In this experiment the use of the in situ technique was evaluated as a tool for predicting voluntary intake and apparent digestibility of forages fed to ruminants. The value of including the rate of passage measurments in prediction equations was particularly examined since very little information was found in the literature on this aspect of the in situ technique.

Residual DM at a single in situ incubation time of 24-h could be used with reasonable accuracy to predict DM digestibility (R^2=0.92) and voluntary intake (R^2=0.79), however, coefficients of determination were not significantly greater than those obtained using the chemical components of the feeds to predict these parameters. Moreover the use of more complex relationships including feed fractions and rate of degradation did not improve the prediction ability of the in situ technique. Although Hovell et al. (1986) and Ørskov et al. (1988) were very positive about the use of the in situ technique in predicting voluntary intake, re-analysis of their

results also demonstrated that voluntary intake could be predicted as accurately from chemical components as from in situ results. In addition it has been shown by Playne et al. (1978) and Mathison et al. (1988) that a large number of bags (greater than 10) are required in order to detect meaningful differences in in situ DM digestibility. In order to obtain 24-h DM residue measurments with a confidence interval of 0.04 at a probability of 0.95 in this experiment 15 bags per replicate would have been required. Thus at the present time, then, the in situ technique is of limited value for use in predicting DM digetibility or voluntary intake of animals fed forage based diets.

This research also indicated that the use of the dynamic parameters of rates of degradation and rates of passage in prediction equations did not result in improvements in prediction of DM digestibility or voluntary intake above that obtained using only results from single in situ incubation times. This is in contrast to the theory proposed by Mertens (1987), that the inclusion of rate constants describing the dynamic parameters of rumen function would increase the ability to describe the variability associated with feeds. A corollary of this observation is that if either voluntary intake or DM digestibility in the animal is known, rates of passage in the animal cannot be predicted accurately using a combination of results from in situ incubations and in vivo digestibility.

The effect of forage quality and feed intake on the passage of fluid and particulate matter through the entire digestive tract was also examined in this experiment. Such rates are probably similar to

rates of passage of material for the ruminoreticulum (Grovum 1984). Rates of passage were reduced when low quality feeds were fed at a low level of intake but at the high level of intake there was no consistent relationship between rates of passage and intake with the better quality feeds. These results are in contrast to those of Owens et al. (1979) and Grovum (1984) who suggested that rates of passage should increase with increasing intake and improved forage quality and suggest that animals adapt to changes in feed qualtity and amounts primarily by regulating of the amount of material in the ruminoreticulm rather than in changing the rate of passage .

In conclusion, this research has demonstrated that, in spite of the current popularity of the in situ bag technique, it is not practical to use it for predicting the voluntary DM intake or digestibility of feed DM in cattle at the present time. It is also apparent that inclusion of information on rates of passage of particulate matter in the animal are of little use in increasing the precision of the in situ technique.

3.1 REFERENCES

Chenost, M., Grenet, E., Demarquilly, C. and Jarrige, R. 1970. The use of the nylon bag technique for the study of forage digestion in thhe rumen and for predicting feed value. Proçeedings of the 11th International Grassland Congress. Surfers Paradise, pp 697-710. University of Queensland Press St. Lucia, Australia.

de Boer, G., Murphy, J. J., and Kennelly, J. J. 1987. Mobile nylon bag for estimating intestinal availability of rumen undegradable protein. J. Dairy Sci. 70:977-982.

Ganev, G., Ørskov, E. R. and Smart, R. 1979. The effect of roughage or concentrate feeding and rumen retention time on total degradation of protein in the rumen. J. Agric. Sci. (Camb.) 93:651-656

Grovum, W. L. 1984. Integration of digestion and digesta kinetics with control of feed intake - a physiological framework for a model of rumen function. In Herbivore Nutrition of the Subtropics and Tropics. (eds F. M. C. Gilchrist and R. I. Mackie), Pretoria, Republic of South Africa.

Hovell, F. D. DeB., Ngambi, J. W. W., Barber, W. P. and Kyle, D. J. 1986. The voluntary intake of hay by sheep in relation to its degradability in the rumen as measured in nylon bags. Anim. Prod. 42:111-118.

Kristensen, E. S., Moller, P. D. and Hvelplund, T. 1982. Estimation of the effective protein degradability in the rumen of cows

using the nylon bag technique combined with the outflow rate. Acta. Agric. Scand. 32:123-127.

Mathison, G. W., Jahn, H. G., Walton, P. D. and Milligan, L. P. 1988. Use of in the in situ technique in the study of degradation of lucerne and smooth bromegrass genotypes. Grass and Forage Sci. 43:474-481.

Mertens, D. R. 1987. Predicitng intake and digestibility using mathimatical models of ruminal function. J. Anim. Sci. 64:1548-1558.

Ørskov , E. R. and McDonald, I. M. 1979. The estimation of protein degradability in the rumen from incubation measurements weighted according to the rate of passage. J. Agric. Sci. (Camb.) 92:499-503.

Ørskov, E. R., Reid, G. W. and Kay, M. 1988. Prediction of intake by cattle from degradation characteristics of roughages. Anim. Prod. 46:29-34.

Owens, F. N., Kazemi, M., Galyean, M. L., Mizwicki, K. L. and Solaiman, S. G. 1979. Ruminal turnover rate - influence of feed additives, feed intake and roughage level. Okla. Agric. Exp. Sta. Rep. MP-104. pp 27-29.

Playne, M. J., Khumnualthong, W. and Echevarria, M. G. 1978. Factors affecting the digestion of oesophageal fistula samples and hay samples in nylon bags in the rumen of cattle. J. Agric. Sci. (Camb.) 90:193-204.

Stern M. D. and Satter, L. D. 1984. Evaluation of nitrogen solubility and the dacron bag technique as methods for estimating protein degradation in the rumen. J. Anim. Sci. 58:714-724.

APPENDIX A

Table 1. Predicition of apparent digestibility (%) of organic matter at the low level of of intake

Equation Number	Equation†	R^2‡	S.E.	Probability
Apparent digestibility of organic matter				
1	27.76 + 2.749(feed %CP)	0.81	6.06	0.003
2	108.8 - 0.865(feed %NDF)	0.92	4.00	0.001
3	115.5 - 1.573(feed %ADF)	0.76	6.81	0.004
4	25.81 + 743.2(Kd)	0.54	9.33	0.020
5	5.21 + 1732.6(Kp)	0.69	7.67	0.007
6	-2.17 + 0.890(A + B)	0.68	7.87	0.008
7	22.03 + 2.192(feed %CP) + 295.4(Kd)	0.86	5.58	0.006
8	111.7 - 0.891(feed %NDF) - 36.1(Kd)	0.92	4.31	0.002
9	109.5 - 1.480(feed %ADF) + 83.08(Kd)	0.76	7.33	0.021
10	24.49 + 2.466(feed %CP) - 212.8(Kp)	0.81	6.52	0.012
11	91.29 - 0.743(feed %NDF) + 347.9(Kp)	0.93	4.06	0.001
12	89.83 - 1.019(feed %ADF) + 855.6(Kp)	0.83	6.12	0.009
13	-7.66 + 0.676(A + B) + 497.8(Kd)	0.88	5.09	0.004
14	-5.43 + 0.482(A + B) + 1020(Kp)	0.78	7.03	0.018
15	3.14 + 1271.3(Kp) + 403.2(Kd)	0.80	6.63	0.016

†Abbreviations used in the equation are as follows: A is the percentage of dry matter which is soluble, B is the percentage of dry matter which is slowly degradable, Kd is the rate of digestion (% h^{-1}) of fraction B, and Kp is the rate of passage (% h^{-1}) of particulate matter measured at the low level of intake, NDF refers to neutral detergent fiber, ADF refers to acid detergent fiber and CP refers to crude protein.

‡Regression relationships based upon nine feeds.

Table 2. Prediction of voluntary dry matter intake

Equation†	R^2‡	S.E.	Probability
DM intake ($kg\ d^{-1}$)			
20.95 - 0.211(feed %NDF)	0.88	1.19	0.001
22.73 - 0.387(feed %ADF)	0.74	1.75	0.005
1.192 + 0.670(feed %CP)	0.77	1.64	0.004
-6.59 + 0.222(A + B)	0.69	1.90	0.007
0.890 + 176(Kd)	0.50	2.45	0.027
-4.87 + 443(Kp)	0.73	1.79	0.005
-7.83 + 0.176(A + B) + 113Kd	0.87	1.36	0.005
-7.45 + 0.117(A + B) + 270(Kp)	0.81	1.62	0.012
22.71 - 21.48(Kd) - 0.226(feed %NDF)	0.88	1.27	0.004
23.18 - 4.76(Kd) - 0.394(feed %ADF)	0.74	1.89	0.026
0.056 + 64.36(Kd) + 0.549(feed %CP)	0.81	1.60	0.011
13.79 + 143(Kp) - 0.161(feed %NDF)	0.91	1.14	0.002
9.53 + 247(Kp) - 0.227(feed %ADF)	0.84	1.48	0.008
-1.33 + 164.1(Kp) + 0.452(feed %CP)	0.79	1.69	0.015
Dry matter intake ($kg^{-0.75}$)			
224.5 - 2.11(feed %NDF)	0.87	12.23	0.001
251.7 - 4.10(feed %ADF)	0.83	14.24	0.002
28.46 + 6.58(feed %CP)	0.75	17.39	0.005
-46.07 + 2.15(A + B)	0.65	20.34	0.010
20.99 + 1855(Kd)	0.55	23.20	0.020
-33.09 + 4421(Kp)	0.73	18.05	0.006
-59.97 + 1.63(A + B) + 1262Kd	0.87	13.61	0.005
-55.40 + 1.01(A + B) + 2829(Kp)	0.79	17.19	0.016
221.7 + 34.28(Kd) - 2.08(feed %NDF)	0.87	13.21	0.004
260.6 - 92.9(Kd) - 4.24(feed %ADF)	0.83	15.36	0.009
12.35 + 831(Kd) + 5.01(feed %CP)	0.81	16.11	0.012
152.4 + 1438(Kp) - 1.60(feed %NDF)	0.90	11.75	0.002
144.3 + 2014(Kp) - 2.80(feed %ADF)	0.90	12.02	0.003
-2.64 + 2020(Kp) + 3.90(feed %CP)	0.77	17.74	0.019

†Abbreviations used in the equation are as follows: A is the percentage of dry matter which is soluble, B is the percentage of dry matter which is slowly degradable, Kd is the rate of digestion (% h^{-1}) of fraction B, and Kp is the rate of passage (% h^{-1}) of particulate matter measured at low level of intake.

‡Regression relationships based upon nine feeds.